TP 9778E

# $CO_2$ REFRIGERATION

# FOR

# LONG-HAUL TRANSPORT

## CONCEPT VIABILITY STUDY AND TESTING OF PROTOTYPES TO ASSESS AND DEMONSTRATE $CO_2$ REFRIGERATION ON LONG-HAUL HIGHWAY REFRIGERATED FREIGHT VEHICLES

FINAL REPORT

by
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FRIDEV

CONCOOL

July 1989

The contents of this report reflect the views of Fridev Refrigeration Systems Inc. and not necessarily the official views or opinions of the Transportation Development Centre of Transport Canada.

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$CO_2$ refrigeration is based on the injection technique (Coldspray) or the vaporization technique (Coldsink). The combination of these two techniques will create a refrigeration system which will be better adapted than mechanical refrigeration units to the long-haul transport of some perishable products. The essential differences between Cryogenic $CO_2$ refrigeration and mechanical refrigeration are thoroughly investigated, including the factors to be taken into consideration to ensure good refrigerated transport. Various approaches have been tried and tested to ensure stable temperature and steady operation when equipment is unattended for a long period of time. A new "Heart and Lung" concept has been developed which permits a regular "Breathing Rhythm" and an appropriate "Blood Pressure" to achieve this result. The same $CO_2$ refrigerated system will be capable of transporting fresh, chilled, frozen, and sub-frozen products; only the consumption of $CO_2$ will vary.

Air turbulence, to accelerate the heat absorption of the system, is created by recuperation of the $CO_2$ gas ejected from the Coldsink to activate a pneumatic motor which is connected to the air blowers. The controls of the new system are electro-pneumatic and permit adjustment based on readings of temperature and pressure sensors, and liquid level switches, which activate the opening and closing of pneumatic valves. In winter, a diesel heater and an electric blower, powered by the alternator of the tractor, send warm air inside the cargo area using the ventilation ductwork. If required, the warm air can be transmitted by the pneumatic blower powered by $CO_2$ gas heated by the diesel heater.

The new system has been developed for application to a 14.4 m trailer equipped with rails for the transport of fresh beef carcasses. The system will have enough capacity to finish cooling down the carcasses during the trip, if required, and cost appears competitive.

$CO_2$ does not affect the ozone layer and could replace Freon for refrigerated transport.

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**16. Résumé** La réfrigération au $CO_2$ est basée sur la technique de l'injection (Coldspray) ou sur la technique de la vaporisation (Coldsink). La combinaison de ces deux techniques doit permettre de développer un système de réfrigération mieux adapté que les unités de réfrigération mécanique pour le transport longue distance de certains produits alimentaires périssables. Les différences essentielles entre les deux systèmes de réfrigération ainsi que les facteurs requis pour obtenir une bonne réfrigération pour les transports ont été analysés en profondeur.

Différentes approches ont été essayées et testées pour garantir la stabilité de la température et une opération continue sans surveillance pendant de longues périodes de temps. Un nouveau concept dénommé "Heart and Lung" a été développé; il permet de garantir ces résultats. Le même système rendra possible le transport de produits frais, refroidis, congelés ou surgelés; seule la consommation de $CO_2$ variera.

Un léger brassage de l'air qui accélère l'absorption de la chaleur, est obtenu en récupérant les gaz $CO_2$ évacués par le système de réfrigération pour activer un moteur pneumatique relié à deux ventilateurs. Les contrôles sont électropneumatiques et permettent tous les ajustements requis automatiquement. Une chaufferette diesel et un ventilateur électrique activés par l'alternateur du tracteur font circuler de l'air chaud en hiver dans le fourgon à travers le réseau de circulation d'air.

Une application du nouveau système a été mise au point afin d'équiper un fourgon de 14.4 m avec des rails pour le transport des carcasses de boeuf frais. Le système de refroidissement a suffisamment de capacité pour permettre de compléter le refroidissement des carcasses de viandes pendant le transport, si nécessaire, dans des conditions particulièrement favorables, et le coût serait compétitif.

Le $CO_2$ n'attaque pas la couche d'ozone et pourrait remplacer le fréon pour le transport réfrigéré.


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## PREFACE

The author of this report, through previous associations, has been directly involved in the development and marketing of the only Canadian patented applications of liquid $CO_2$ for Cryogenic Refrigeration applied to the transport industry. Reference is made herein to the Thermotrol from Galt Equipment and then to the Concool Systems.

When it learned that the Canadian government was seriously interested in learning more about the possible applications of this technology to the refrigerated transport of perishable products, such as red meat, fish, poultry, and fresh produce, Fridev Refrigeration System Inc. was very interested in meeting this challenge.

Subsequently, after negotiating an agreement with Concool Refrigeration Ltd., which held several patents on $CO_2$ Cryogenic applications, an unsolicited proposal was prepared and presented to Supply and Services Canada (DSS), to find a solution for the highway and intermodal aspects of the transportation industry, since it was felt that it was in these sectors that Cryogenic $CO_2$ Refrigeration would prove most beneficial.

In November 1985, Fridev-Concool received the mandate to carry out this project.

## SUMMARY

Mechanical refrigeration is now the standard for refrigerated transport, however, the method used to obtain the refrigeration inside the cargo box is contrary to the basic principles of refrigeration. A transport vehicle is not a processing plant, and even less a chilling tunnel. It is supposed to be a holding room where products are maintained at the temperature at which they have been received, for the period of transportation.

A holding room has to be well insulated (most trailers are not) to stop the penetration of heat from the outside. It has to have a uniform temperature throughout, and must have the ability to absorb quickly any heat without affecting the quality of the stored product. Most mechanical refrigeration units currently used on transport equipment cannot do this, but Carbon Dioxide ($CO_2$) refrigeration can do it very efficiently if properly used. Unfortunately, it is not a simple task.

Injection is the simplest way of creating cold with $CO_2$. It consists of spraying liquid $CO_2$, kept under pressure and at low temperature, into a space at atmospheric pressure. Immediately, dry snow (solid $CO_2$) and $CO_2$ vapors at -78°C (-110°F) are formed. As the dry snow sublimates, it delivers 571 kJ/kg (246 Btu/lb) of snow, or 278 kJ/kg (120 Btu/lb) of liquid $CO_2$ injected. But this technique does not guarantee a uniform temperature. It can be much too cold when in direct contact with sensitive products and it rarifies the oxygen in the environment causing problems to human beings and to some perishable products which are still "alive" and "breathing". For these reasons, the injection technique is primarily used for freezing.

Another technique developed by Concool Refrigeration Ltd - Pointe-Claire, called the Coldsink approach, involves recuperating the latent heat obtained when liquid $CO_2$ converts to gas $CO_2$ inside a closed pipe system. It permits an exact control of the surrounding temperature through a precise control of the pressure inside the Coldsink. Venting of excess gas pressure re-establishes immediately the desired pressure and, consequently, temperature.

An appropriate combination of these two techniques was expected to provide the type of refrigeration needed for better refrigerated transport.

The original concept developed by Fridev Refrigeration Systems Inc - St-Lambert, consisted in surrounding the complete cargo box with a wrap-around Coldsink inside the walls which would absorb the heat from the outside before it penetrated inside the cargo space. This first concept was abandoned after a thorough heat transfer study, conducted by Dr. Charles Murphy and Brian Mori of McGill University, suggested that the expected results would not

be obtained, and that the temperature would be unequal as the liquid could not circulate evenly everywhere inside this piping system.

It was then decided to replace the Wrap-around Coldsink by a jacketed space similar to a standard jacketed storage. The cold barrier would be obtained by injecting liquid $CO_2$ inside the voids in the floor, walls and roof, as the $CO_2$ vapors disperse so quickly, and the Coldsink would be located only under the void in the roof.

A full size laboratory prototype was built to conduct significant experiments. The jacketed concept did not work, as it became impossible, despite several attempts, to move the cold air fast enough inside the floor and inside the walls. On the other hand, the Coldsink in the roof gave excellent heat absorption results in spite of defective construction. After improving the heat absorption of the ceiling, a pneumatic blower was installed inside the cargo area. The heat transfer and the uniformity of the temperature were increased considerably.

Problems with the constant refilling of the Coldsink were experienced as, after a time, the pressure spread between the Coldsink and the Reserve tank was so great that the transfer of liquid $CO_2$ became impossible, making it unrealistic to guarantee the operation of the system for long periods of time.

The various tests and experiments conducted progressively gave the researchers a more complete understanding of the interrelation between pressures, temperatures, and liquid levels of $CO_2$ inside the Coldsink and the Reserve tank, and temperatures between the Coldsink and the cargo area. This understanding was required to resolve the problems at hand.

The new "Heart and Lung" concept which was finally developed consists of establishing a regular "Breathing Rhythm" and an appropriate "Blood Pressure" for the system. "Breathing Rhythm" is established by the automatic setting of a maximum and minimum pressure inside the Coldsink. The controls open and close the gas vent of the Coldsink to release the excess pressure at the appropriate time and level. "Blood Pressure" is established by the automatic regulating of the pressures inside the Coldsink and the Reserve tank, to obtain appropriate refilling of the Coldsink regardless of the temperature at which the system operates.

The gas ejected from the Coldsink is utilized to cool down the floor and to supply a pneumatic motor which activates two air blowers. If the amount of gas is small, because of limited heat absorption, only one blower will operate at low speed. If the amount of gas is very large because of very important heat absorption, then the two blowers will operate at full capacity. The air from the blowers is circulated inside the cargo area, alongside the full length of the trailer, close to the floor.

During the winter months, a small diesel heater will distribute warm air inside the cargo area using exactly the same ducting system as the air turbulence, assisted by one of the blowers for uniform heat circulation. If the trailer is connected to the tractor, it is the alternator of the tractor which will activate an electronic motor which activates the blower and lights the glow of the heater. If the trailer is not connected, or if the tractor motor is stopped, then the pneumatic blower will recharge the battery to ensure the regular supply of electric power for the heater glow.

Originally, the intent was to have a fully pneumatic control system. Experiments and tests have demonstrated that pneumatic controls are difficult to adjust with precision on the road, and could be disturbed by the vibration of the vehicle. It was decided, reluctantly, to switch to an electronic control system to activate the opening and closing of the pneumatic valves, to adjust the pressures according to the existing inside-temperature compared to the preset temperature, and to determine the pressure spreads between maximum and minimum pressure of the Coldsink and maximum pressure of the Reserve tank. The electronic control card now gives the system a level of accuracy which could not have been expected from a pneumatic system. The consumption of power is very small, considering that the hard work is done by pneumatic control valves, and that only the signals are electronic.

Each Reserve tank contains 450 kg. of liquid $CO_2$. The number of tanks will depend on the need for autonomy of the vehicle, but the weight of each tank filled with liquid $CO_2$ will eventually affect the transport capacity of the trailer.

It was agreed during the advisory committee meeting of October 7, 1987, that the final engineering design of the system should be done for the transport of fresh beef carcasses, as this very perishable product could most benefit from the quality of refrigeration supplied by the new Cryogenic $CO_2$ refrigeration system.

The fresh beef-carcasses trailer is equipped with enough heat absorption capacity that it is possible to finish cooling the beef during the trip, if so desired by the shipper, without affecting at all the quality of the meat. Of course, the consumption of $CO_2$ will necessarily increase according to the additional heat to be absorbed.

A complete simulation model has been developed at McGill University; and it produces exactly the results anticipated. The inside temperature remains extremely stable, regardless of the outside temperature. The air turbulence is always proportional to the amount of heat to be absorbed so that the heat does not remain around the product before being absorbed by the Coldsink.

The cost of a prototype of this new system is obviously very high compared to the cost of a Thermoking or Carrier with equivalent capacity, but this is to be expected for a prototype. It is believed that, because of the simplicity of the system, and after a thorough value analysis has been performed, the cost of the equipment could be reduced to half of the present price, which would make it very competitive with any mechanical system of comparable capability.

As expected, the cost of operation over one year would not be any higher that the cost for a mechanical refrigeration system especially if the system operates inside very extreme temperature conditions. The cost of maintenance should be much lower due to the simplicity of the system.

Finally, the timing of this research could not be better, if we consider the latest decisions to ban the use of Freon during the coming years. Liquid $CO_2$ does not pollute the enviroment. It is available in large quantities. Its price could definitely be reduced if consumption were more stable, and availability for highway use would present no difficulties if sufficient demand existed.

## SOMMAIRE

La réfrigération mécanique est actuellement le standard pour les transports réfrigérés, même si la méthode utilisée pour produire cette réfrigération va à l'encontre de tous les principes de bonne réfrigération. En effet, un véhicule de transport n'est pas une usine de transformation et encore moins un tunnel de refroidissement. Il est supposé être un entrepôt temporaire où les produits sont maintenus à la température à laquelle ils ont été reçus et cela durant toute la durée du transport.

Un entrepôt doit être bien isolé afin d'arrêter le plus possible la pénétration de la chaleur extérieure, or la plupart des camions réfrigérés ne sont plus vraiment isothermes. De plus, il doit maintenir une température uniforme et doit pouvoir rapidement absorber toute chaleur qui pourrait pénétrer à l'intérieur, sans pour autant affecter la qualité du produit entreposé. La plupart des unités de réfrigération mécanique utilisées sur les véhicules de transport n'ont pas le potentiel pour faire tout cela. La réfrigération au $CO_2$ serait apte à le faire très efficacement si elle était contrôlée adéquatement. Malheureusement, ce n'est pas une affaire simple.

L'injection est la méthode la plus facile de créer du froid avec du $CO_2$. Cela consiste à diffuser du $CO_2$ liquide maintenu sous pression et à basse température, dans l'air à la pression atmosphérique. Le $CO_2$ liquide se transforme immédiatement en neige carbonique ($CO_2$ solide) et en gaz carbonique à -78°C. Lorsque la neige carbonique se sublime, elle dégage 570 kJ/kg. Mais cette technique ne garantit pas une température uniforme et peut créer un froid beaucoup trop intense lorsque mis en contact avec des produits délicats. De plus, elle raréfie l'oxygène dans l'environnement ce qui peut causer des problèmes aux humains et aux aliments qui respirent. La technique de l'injection est donc surtout utilisée pour la surgélation des aliments.

Une autre technique développée par CONCOOL REFRIGERATION LTD. de Pointe Claire, consiste à récupérer la chaleur latente de vaporisation obtenue lorsque le $CO_2$ liquide se transforme en $CO_2$ gazeux à l'intérieur d'un système de tuyauterie fermé. Cette chaleur latente peut absorber 276 kJ/kg de $CO_2$ liquide. Cette caractéristique permet de contrôler la température avec grande précision en contrôlant la pression à l'intérieur d'un échangeur de chaleur appelé "Coldsink". Lorsque l'excédent de pression généré par la création du $CO_2$ gazeux est évacué, la température est immédiatement rétablie à la température désirée.

Une combinaison appropriée de ces deux techniques doit permettre à FRIDEV REFRIGERATION SYSTEMS INC. de ST-Lambert,de mettre au

point un système de réfrigération mieux adapté aux transports routiers des produits alimentaires périssables.

Le concept original mis de l'avant par FRIDEV consistait à envelopper entièrement la boîte du véhicule isotherme avec un "Coldsink" qui formerait une barrière contre toute pénétration de chaleur venant de l'extérieur et qui serait absorbée par le "Coldsink" avant même de pénétrer dans la boîte. Ce premier concept fut abandonné après une étude de transfert de chaleur réalisé par le Dr. Murphy de McGill. L'étude fait ressortir que la température à l'intérieur de la boîte deviendrait rapidement très inégale, car le liquide circulerait difficilement à travers le réseau et n'assurerait pas une protection absolue contre la pénétration de la chaleur.

La décision prise fut donc de remplacer l'enveloppe "Coldsink" par une enveloppe d'air froid similaire à la technique utilisée pour les "Jacketed Storages". La barrière de froid serait obtenue en injectant du $CO_2$ liquide à l'intérieur de l'enveloppe dans le plancher, les côtés et le toit, et le "Coldsink" ne serait placé que dans le plafond en dessous de l'espace vide du toit. Afin de réaliser des expériences significatives, un prototype à pleine grandeur fut construit. Le concept "Jacketed" ne fonctionna pas comme espéré, car il devint impossible de faire circuler l'air froid assez rapidement et efficacement pour obtenir le résultat attendu. Par contre, le "Coldsink" dans le plafond s'avéra un excellent instrument pour absorber l'air chaud ascendant, malgré les faiblesses de contruction et les mauvais contacts.

Le pouvoir d'absorption du "Coldsink" ayant été amélioré et après l'installation d'un ventilateur pneumatique à l'intérieur de la boîte, la capacité d'absorption de l'équipement était excellente ainsi que l'uniformité de la température dans la boîte. Par contre, le remplissage du "Coldsink" représentait d'importants problèmes, car après un certain temps, la différence de pression entre le "Coldsink" et le réservoir de réserve était trop grande pour permettre un transfert rapide et complet du $CO_2$ liquide. La conséquence était que le "Coldsink" se vidait, et que le pouvoir d'absorption diminuait considérablement.

De multiples tests et essais ont permis aux chercheurs de contrôler progressivement l'interrelation existant entre les pressions, les températures et les niveaux de $CO_2$ liquide pour enfin envisager le contrôle du système.

Un nouveau concept "Heart and Lung" fut alors mis au point; il consiste à établir un rythme régulier de "respirations" et une pression appropriée à travers tout le système. Le rythme des respirations est établi en réglant automatiquement les niveaux de pression maximum et minimum entre lesquelles le "Coldsink" travaillera pour obtenir la température voulue. Lorsque le niveau maximum est atteint, une vanne laisse échapper l'excès de

gaz $CO_2$, et se referme lorsque la pression minimum est atteinte. La pression adéquate est réalisée en réglant automatiquement les pressions dans le "Coldsink" et dans le réservoir de réserve afin d'obtenir en permanence le remplissage du "Coldsink" à toutes les températures d'opération possibles.

Le gaz éjecté du "Coldsink" lors d'une respiration est utilisé pour refroidir le plancher et pour faire tourner un moteur pneumatique qui entraîne deux ventilateurs d'air.
Si la quantité de gaz est basse parce que la chaleur à absorber est faible, un ventilateur seulement fonctionne à petite vitesse. Si la quantité de gaz est élevée parce que la chaleur est grande, les deux ventilateurs enverront un courant d'air tout le long de la base des côtés de la boîte.

En hiver, une petite chaufferette au diesel distribuera de l'air chaud à travers la même canalisation de circulation d'air, et sera assistée par un ventilateur pour uniformiser la circulation de la chaleur. Si la boîte isotherme est attachée au tracteur, l'alternateur du tracteur activera un moteur électrique pour faire tourner le ventilateur et allumer le diesel de la chaufferette. Si la boîte est détachée du tracteur ou si le tracteur est arrêté, c'est le moteur pneumatique qui activera le ventilateur et l'alternateur de la batterie du véhicule et qui allumera le diesel de la chaufferette.

Au départ, l'intention était d'avoir un système uniquement à contrôle pneumatique. Les expériences et les tests ont démontré que le réglage des contrôles pneumatiques était très difficile à faire sur la route avec précision et que de plus, les vibrations pouvaient dérégler les contrôles. C'est avec réticence qu'il a été décidé d'adopter un système de contrôles électroniques afin d'activer les valves pneumatiques, pour ajuster les pressions automatiquement en fonction des températures, et pour déterminer les écarts de pression requis pour les différents équipements. La carte de contrôle électronique permet maintenant de donner une précision qui n'aurait jamais pu être atteinte avec un système purement pneumatique. La consommation d'électricité est très faible puisque tous les travaux sont faits pneumatiquement et seuls les signaux sont électroniques.

Les réservoirs de réserve contiennent 450kg de $CO_2$ liquide chacun. Le nombre de réservoirs installés dépendra de l'autonomie requise, mais le poids du liquide transporté sera évidemment un handicap pour la capacité de transport du véhicule.

Lors de la réunion du comité consultatif du 7 octobre 1987, il a été décidé de réaliser les dessins d'atelier du système pour adaptation au transport des carcasses de boeuf frais, étant donné que ce type de transport est très délicat et qu'il bénéficierait au maximum des avantages du nouveau système de réfrigération au $CO_2$.

La remorque destinée au transport des carcasses de boeuf est équipée avec suffisamment de capacité d'absorption de chaleur pour envisager de terminer le refroidissement des carcasses pendant le transport, mais cette fois dans des conditions de refroidissement parfaitement acceptables pour la qualité de la viande. Naturellement, cela représentera une augmentation de consommation de $CO_2$ et donc du coût d'opération.

Une simulation informatique a été réalisée à McGill et reflète avec exactitude les résultats anticipés. La température intérieure demeure parfaitement stable, et la turbulence de l'air est toujours proportionnelle à la quantité de chaleur qui doit être absorbée, de manière à ce que la chaleur ne reste pas en contact avec le produit avant d'être absorbée par le "Coldsink".

Le coût du prototype est évidemment très élevé comparé au coût d'un appareil de réfrigération mécanique de série ayant la capacité d'opérer le même travail à l'année longue. Mais il faut s'attendre à un tel résultat étant donné qu'une analyse de valeur n'a pas été faite pour identifier des équipements de substitution à ceux actuellement retenus. La simplicité du système, et le fait d'utiliser essentiellement des éléments fabriqués en série, permettra de réduire considérablement le coût lorsque le système sera construit en quantité, ce qui le rendra très compétitif.

Tel que prévu, le coût d'opération sur la durée d'une année ne sera pas plus élevé qu'un système de réfrigération mécanique, surtout si le système est utilisé dans un climat ou les extrêmes de température durant l'année sont élevés. Le coût de maintenance, qui ne peut être évalué actuellement, devrait être très inférieur étant donné la simplicité du système.

Est-il besoin d'ajouter que les problèmes actuels causés à la couche d'ozone par la fabrication du fréon, ne peuvent qu'aider ce nouveau système à faire ses preuves. Le $CO_2$ liquide ne pollue pas l'environnement et il est disponible en grande quantité. Le prix pourrait diminuer si l'utilisation se généralise à l'année longue et la disponibilité du produit sur les autoroutes ne sera pas un problème lorsque la demande sera là.

# TABLE OF CONTENTS


| | | Page |
|---|---|---|
| INTRODUCTION | | 1 |
| PART I - INDUSTRY STUDY | | 5 |
| 1. | Carbon Dioxide - $CO_2$ | 5 |
| | 1.1 What is $CO_2$ ? | 5 |
| | 1.2 Availability of Liquid $CO_2$ in Canada | 7 |
| | 1.3 Cryogenic $CO_2$ Refrigeration | 8 |
| | 1.3.1 Injection technique | |
| | 1.3.2 Vaporization technique | |
| | 1.4 Manufacturing Standards, Laws and Regulations | 11 |
| 2. | Cryogenic $CO_2$ Refrigeration versus Mechanical Refrigeration | 13 |
| | 2.1 Functioning of a Mechanical Refrigeration System | 13 |
| | 2.1.1 The heat exchanger | |
| | 2.1.2 The blower | |
| | 2.1.3 The compressor and Freon refrigerant | |
| | 2.1.4 The diesel motor | |
| | 2.2 Advantages of Mechanical over Cryogenic Refrigeration | 15 |
| | 2.2.1 Constant very high temperatures | |
| | 2.2.2 Very irregular transport patterns | |
| | 2.2.3 Products transported at very high temperatures | |
| | 2.3 Advantages of Cryogenic over Mechanical Refrigeration | 16 |
| | 2.3.1 Irregular, extremely high temperature | |
| | 2.3.2 Flexibility in refrigeration level | |
| | 2.3.3 Regular transport patterns | |
| | 2.3.4 Products which suffer from excess ventilation and/or benefit from $CO_2$ environment | |
| 3. | Considerations for good Refrigerated Transport | 18 |
| | 3.1 Environmental conditions | 18 |
| | 3.1.1 Temperature requirements | |
| | 3.1.2 Climatic environment | |
| | 3.2 Importance of Dt in Refrigerated Transport | 19 |
| | 3.2.1 Maximum extreme Dt's | |
| | 3.2.2 How mechanical units adapt to the fluctuations in Dt in relation with the U factor of the box | |
| | 3.2.3 High, low and mean temperatures per day, month, year | |
| | 3.3 Transport regulations | 22 |
| | 3.4 Appropriate isotherm vehicles | 22 |
| | 3.4.1 Insulation material | |
| | 3.4.2 Material for the body | |
| | 3.4.3 Construction techniques | |
| | 3.4.4 Air infiltration | |
| | 3.4.5 Ventilation vs air circulation and air turbulence | |
| | 3.4.6 Doors | |

3.5 Characteristics of a good Refrigeration System 25
3.5.1 Ability to maintain temperatures
3.5.2 Ability to pre-cool or re-cool cargo space at a predetermined level
3.5.3 Ability to decrease temperature of the product to a predetermined level and maintain it
3.5.4 Ability to cope with humidity
3.6 Sound Transportation Procedures 28
3.6.1 Loading and unloading
3.6.2 Pre-cooling
3.6.3 Stacking techniques
3.6.4 Packaging technology
3.6.5 Door opening and closing
3.6.6 Preventive and regular maintenance

4. Characteristics and importance of refrigerated transport in Canada plus additional potential in North America 30

4.1 What is meant by perishable food products? 30
4.2 What is meant by refrigerated transport ? 30
4.3 Refrigerated transport in Canada 31
4.3.1 Importance
4.3.2 Local transport
4.3.3 Long-haul transport
4.3.4 Transporters
4.4 Characteristics of current long-haul refrigerated transport 32
4.4.1 "Bigger and bigger every day"
4.4.2 Drawbacks
4.5 Importance of long-haul refrigerated transport of perishable food products in Canada 34

**PART II - TECHNICAL STUDY AND TESTING** 37

5. Preliminary Conceptualization (March 14, 1986) 37

5.1 Techniques used 37
5.1.1 The Coldspray
5.1.2 The Coldsink
5.1.3 The liquid $CO_2$ Reserve
5.2 The wrap - around Coldsink concept 39
5.3 Theoretical study by Dr. Charles Murphy and Brian Mori of McGill University 40

6. New concept (June 27, 1986) and laboratory prototype testing 42

6.1 The straight-forward jacketed concept 42
6.2 Laboratory test trailer selection 42
6.3 Container conversion 43
6.4 The Cryogenic Refrigeration 44

6.5 The heating system 45
6.6 Testing equipment and programs 45
6.7 Testing of the system 46
6.7.1 Results on pressure drop and pressure recovery
6.7.2 Results on cold transfer sensitivity

7. Modification to the Concept (February 1987) and Road Prototype Testing 50

7.1 New design for the floor and wall voids 50
7.1.1 Rebuilding the floor
7.1.2 Rebuilding of the walls
7.2 Installing a pneumatic blower in the floor void 51
7.3 Installing a diesel heater 51
7.4 Reinstalling the Coldspray 52
7.5 Reinstalling the measuring devices 52
7.6 Testing the modified prototype 53
7.6.1 Tests on air circulation in the voids
7.6.2 Tests on cooling with the Coldsink - Coldplate
7.6.3 Tests on the pressure drop in the $CO_2$ Reserve tank
7.6.4 Tests on the filling and closing of the Coldsink
7.7 Analysis of the Test results and interpretation 56
7.7.1 The jacketed approach is unacceptable
7.7.2 The inside air turbulence is of prime importance
7.7.3 The Coldsink - Coldplate must be improved

8. Modification of the Concept (July 15, 1987) and additional testing of the Road Prototype 59

8.1 Removing the void in the floor 59
8.2 Installing a pneumatic blower inside the cargo space 59
8.3 Improving the heat absorption capacity of the Coldsink - Coldplate 60
8.4 Reinstalling the measuring devices 60
8.5 New tests on the rebuilt prototype 61
8.6 Results of cooling tests 62
8.7 Results of ventilation tests in the prototype 62
8.8 Tests to control the pressure inside the Reserve tank 62
8.9 Solutions to the various problems 63

**PART III THE SYSTEM DEVELOPED AND ITS APPLICATION TO THE TRANSPORT OF FRESH BEEF CARCASSES** 65

9. The "Heart and Lung" Concept 65

9.1 The new heat absorption system 65
9.2 The controls of the "Heart and Lung" functions 66
9.3 The purpose of the "Breathing Rhythm" 67
9.4 The importance of the "Blood Pressure" 67

9.5 The heating system 68
9.6 The electronic controls 68
9.7 Pre-chilling, Re-chilling and Sub-freezing 69
9.8 The computor simulation model 69
9.8.1 Testing runs
9.8.2 Use of the simulation model
9.9 Conclusion 70

10. Costing of the system 72

10.1 Capital cost 72
10.2 Cost of operation 74
10.2.1 Factors affecting consumption
10.2.2 Costs based on $CO_2$ price per ton
10.2.3 Autonomy
10.3 Comparative cost with a large diesel unit 75
10.4 Cost of maintenance 76

11. Adaptation of the new concept to the transport of fresh beef carcasses 78

11.1 Difficulties encountered in transporting fresh beef carcasses 78
11.2 Reasons for selecting the transport of fresh beef carcasses 80
11.3 Criteria to be observed 81
11.3.1 Hanging tracks
11.3.2 Carcasses
11.3.3 Load weight
11.3.4 Heat absorption capability of the system
11.3.5 Air turbulence capability of the system
11.3.6 Heating requirement
11.4 Liquid $CO_2$ Reserve 83
11.5 Development of the Final Industrial Design 83

12. CONCLUSION 84

## GRAPHS AND FIGURES


| | | Section | After Page |
|---|---|---|---|
| 1 | Wrap-around Coldsink Concept 3/86 | 5.2 | 40 |
| 2 | Revised concept 6/86 | 6.1 | 42 |
| 3 | Sample data logger plots | 6.6 | 46 |
| 4 | Sample prologger data files | 6.6 | 46 |
| 5 | Coldsink pressure drops and recovery time | 6.7.1 | 48 |
| 6 | Coldsink pressure drops - various sensitivities | 6.7.2 | 48 |
| 7 | Coldspray pressure drops - various timings | 6.7.2 | 48 |
| 8 | Coldspray pressure drops with short intervals | 6.7.2 | 48 |
| 9 | Floor duct - fishbone design | 7.1.1 | 50 |
| 10 | Finned pipes inside roof void | 8.3 | 60 |
| 11 | Simulation model 120 seconds | 9.8 | 70 |
| 12 | Simulation model 3600 seconds | 9.8 | 70 |
| 13 | Simulation model 7200 seconds | 9.8 | 70 |
| 14 | Simulation model 1 vent | 9.8.1 | 70 |
| 15 | Simulation model 2 vents | 9.8.1 | 70 |
| 16 | Simulation model 4 vents | 9.8.1 | 70 |
| 17 | Comparative operation costs for Sub-cooled products | 10.3 | 76 |
| 18 | Comparative operation for Frozen products | 10.3 | 76 |
| 19 | Comparative operation for Fresh products | 10.3 | 76 |

## INTRODUCTION

Carbon Dioxide ($CO_2$) as a gas is a major component of our atmosphere. For many years, no one paid much attention to this gas which was omnipresent and an intrinsic part of life on earth. Today, since the problem of the "greenhouse effect" has been identified, a lot is said about the damaging effect of excess $CO_2$, and it will be necessary to return to this subject later on during the study. However, many people are now aware of the existence of $CO_2$ even if they are not very familiar with it. This might help generate interest for its applications and benefits.

It was only about one hundred years ago that the idea of using this gas for creating carbonated beverages resulted in the industrial production of $CO_2$ and it was only much later that the properties of $CO_2$ as a refrigerant under the name of "dry ice" began to be considered as a practical alternative to hydride ice. Now, gazeous, liquid, or solid Carbon Dioxide is used for many industrial applications. One of them is Cryogenic $CO_2$ Refrigeration. The term might not be exact as the low temperatures generated by $CO_2$ are not scientifically low enough to be classified as Cryogenic. However, for everyday use, it is a convenient word to distinguish this type of refrigeration from others which do not have the ability to reach such low temperatures.

Cryogenic $CO_2$ Refrigeration is extensively used in the food industry for obtaining fast freezing. $CO_2$ freezing tunnels, or cabinets, permit the freezing of fresh products much faster than any mechanical system. Solid $CO_2$ blocks, made of compressed dry snow, have been used extensively to keep products cooled for much longer than hydride ice ever could. Lately, Gas $CO_2$ inserted in an airtight bag, is used more and more to extend the shelf life of fresh products such as poultry or fish. Liquid $CO_2$ has been used on occasion for refrigerated transport, but acceptance by the industry has been very slow for several reasons. An important reason is that the manufacture of the required portable units is totally controlled by two major manufacturers of mechanical units, THERMOKING and CARRIER.

Other reasons have to do with the availability of liquid $CO_2$, with its cost, and with the weight of the fuel to be transported on board, but also, and perhaps more importantly, with the difficulties encountered in properly utilizing this product to exploit the viable applications.

As $CO_2$ is very cold, special precautions have to be taken to avoid contact with fresh products. Also, as $CO_2$ is oxygen-absorbing, special care has to be taken when putting it in contact with human beings or with products which are still "alive" and "breathing". Finally, since it is relatively expensive and bulky, $CO_2$ should not be wasted.

The study reported here proposed to demonstrate that the apparent disadvantages of this product can be turned to great advantage

when $CO_2$ refrigeration is properly controlled and harnessed. This is not to say that Cryogenic $CO_2$ Refrigeration can resolve all the problems facing the refrigerated transport industry, nor that it is appropriate to consider it for the transportation of every type of perishable food product. But it is believed that, if properly handled, $CO_2$ can become an extremely valid alternative to mechanical refrigeration when used on long-haul, or even short-haul, road transport of some specific commodities, be they fresh, chilled or frozen, as well as for intermodal transport equipment or even railroad shipping.

Spoilage in transit has always been a major concern for the food industry. Despite this, it became apparent when studying this problem, that those responsible for each stage in the transport of perishable goods have a tendency to take chances, hoping that there will be no accident even if safety factors are regularly ignored.

Some examples are:
- Products are not brought to the proper temperature before being shipped, or they may have already started to spoil.
- Products are packed in boxes which do not allow proper ventilation or refrigeration in transit.
- Products are improperly loaded or stacked, and obstruct ventilation
- The insulation of the vehicle is inadequate.
- The air stream which carries the cooled air through the vehicle is either much too strong or totally nonexistent.

In fact, everyone is quite ready to cast the blame on others and very few are willing to recognize their negligence, let alone their errors. Consequently, insurance claims mount, premiums increase, and many worry about the quality of refrigerated transport. But the problems remain unsolved. No refrigeration system is perfect and each one has characteristics which make it more desirable for some applications and less desirable for others. Mechanical Refrigeration is quite acceptable for refrigerated transport as long as it is not used indiscriminately and as long as the weak points of the system are not covered up or presented as advantages to unsuspecting users.

The purpose of this study is to identify when Cryogenic $CO_2$ Refrigeration could advantageously replace Mechanical Refrigeration. The objective, then, is to define precisely in which cases and what has to be done to insure a practical alternative, and finally to offer a solution which would be economically acceptable. The following report documents the path followed, and the very positive conclusion of this research.

Much reading and many meetings with people in the industry, or concerned with refrigerated transport, have made it possible to identify the factors to be taken into consideration to obtain good refrigerated transport. Then, by comparing Cryogenic and Mechanical Refrigeration, it became relatively easy to ascertain when $CO_2$ refrigeration had an edge over Mechanical Refrigeration, and to identify the weaknesses of $CO_2$ Refrigeration which had to

be overcome before the system could be utilized. After an overview of the importance of the market of refrigerated transport equipment and the availability of $CO_2$, the report presents an explanation of the technical research. A computer simulation and a full size prototype were used for the theoretical and practical verification of the system. To ensure that the research would be practical and significant, it was decided that the final design and engineering should be made for a specific application. The transportation of fresh beef carcasses was selected; this is a complex example requiring precise technology which many transporters are reluctant to undertake.

Specific criteria and parameters were developed to meet these requirements. The system is elaborate and permits the proper transport of fresh beef carcasses on long- and short-hauls, in summer as well as winter. Adequate ventilation is provided not only to deliver the meat in the best possible condition, but also to cool it during transport, if required. The complete system is pneumatically operated and electronically controlled to maintain the product at a stable temperature of ± 1°C. The cost and weight of the system have been of prime concern throughout the study, and, in some instances, trade-offs will be required.
Prime quality of meat and safety of operation have been the leading concerns of this study, while protection of the environment is an additional and timely advantage of the system.

## PART I - INDUSTRY STUDY

It is important to begin by understanding what Carbon Dioxide is, what it can do, and what it costs. Second, it is important to compare a Cryogenic $CO_2$ Refrigeration system with a Mechanical Refrigeration system (the current standard on most transport vehicles). Then factors which make for good refrigeration must be identified to ascertain whether or not the proposed system could make a significant contribution to the refrigerated transport field. Finally, an appreciation of the importance of this industry in the Canadian economy will place this new system in the proper context.

### 1. CARBON DIOXIDE - $CO_2$

#### 1.1 What is $CO_2$ ?

Carbon Dioxide ($CO_2$) is a major component of our atmosphere; the normal concentration is 0.03 per cent per volume. At normal atmospheric temperatures and pressures, Carbon Dioxide gas is colorless, odorless and about 1.5 times as heavy as air. Carbon Dioxide gas is non-reactive and non-toxic. It will not burn and it will not support combustion or life. $CO_2$ gas is generated by combustion of fossil fuels and by many industrial processes.

The first commercial application was the use of purified gaseous Carbon Dioxide to carbonate soft drinks. The purified gases were later liquified or solidified for new applications; among these was refrigeration.

In the past, the manufacturing of liquid $CO_2$ was done by burning fossil fuels and then by liquefying and purifying the gas $CO_2$ obtained at 99.9 per cent or better, inside pressure vessels maintained at -20°C (-4°F) and 18 bars (270 psi) or lower. This type of manufacturing plant still exists in underdeveloped countries but increasingly has been replaced, in North America and Europe, by very large new liquifying plants which recuperate the emanations of gas $CO_2$ from hydrocarbon refineries, fertilizer manufacturers, or fermentation industries. The cost of production is much cheaper, and the price of liquid $CO_2$ has barely doubled in 20 years. The competition among manufacturers is fierce. Meanwhile, the cost of fossil fuels, such as diesel, has increased so much during this same period that it now becomes possible to compare the relative cost of liquid $CO_2$ as a refrigerant, to that of diesel fuel when used for operating a Mechanical Refrigeration unit mounted on a transport vehicle.

The liquifying and purifying processes are now done electrically, no longer by combustion, and consequently these new factories are definitely helping to fight air pollution by recycling the $CO_2$ gas which would otherwise be released, unused, in the air.

The normal concentration of $CO_2$ in the atmosphere is 0.03 per cent per volume but, since $CO_2$ gas is generated by the combustion of fossil fuels and by many industrial processes, and emission are often unchecked, it is not unusual to find concentrations as high as 0.5 per cent. Over 1.0 per cent concentration for 10 continuous hours or 3.0 per cent for 10 minutes is hazardous to health.

(Recently, many people have become very concerned with the "greenhouse effect" which threatens our planet. Excessive $CO_2$ emanations are regularly mentioned as one of the major culprits. It is very important at this stage to make the distinction between uncontrolled, wasteful emanations of $CO_2$ gas and the recycling of $CO_2$ to get maximum use of its properties before it is returned to the atmosphere.)

The properties of Carbon Dioxide which make this product attractive for sound refrigeration are as follows:

- At a very low temperature (-56°C or -70°F), and at a pressure of 4 bars (60 psi), Carbon Dioxide may exist simultaneously as a solid, liquid and gas. This is called the triple point.
- Below this temperature or this pressure, Carbon Dioxide cannot be a liquid.
- Above what is called the critical point (31°C or 88°F) Carbon Dioxide, inside a closed container, cannot exist as a liquid regardless of the pressure.
- At temperatures and pressures above the triple point and below the critical point, Carbon Dioxide liquid and gas may exist in equilibrium in a closed container.
- Within this temperature range, the pressure in a closed container holding Carbon Dioxide liquid and gas in equilibrium, bears a definite relationship to the temperature.
- At temperature and pressures below the triple point, Carbon Dioxide may be either a solid (dry ice) or a gas.
- Solid Carbon Dioxide, at a temperature of -78.5°C (-109°F) and at atmospheric pressure, sublimates to a gas without passing through the liquid phase.

All these properties are fundamental to Cryogenic $CO_2$ Refrigeration. It is the exact and appropriate use and control of Carbon Dioxide, primarily in liquefied form, which will permit the development of dependable refrigeration systems.
Currently, Carbon Dioxide is available from manufacturers as liquid $CO_2$ or in solid blocks of dry ice at -79°C (-109°F) weighing 1560 kg/m$^3$ (97 lb/ft$^3$) and having a latent heat of 571 kJ/kg (246 Btu/lb).

## 1.2 Availability of Liquid $CO_2$ in Canada

The manufacturing of liquid $CO_2$ for industrial use only is under consideration here. The manufacturing capacity of liquid $CO_2$ in Canada is much greater the current needs but consumption is not uniform during the year. This makes marketing of this product quite complex.

The name plate capacity of production in Canada is 2645 metric tons/day or a potential annual capacity of 700,000 metric tons. New $CO_2$ manufacturing plants recuperate $CO_2$ gas from old refinery plants which produce clean $CO_2$, or from new fertilizer plants which have a lot of unused clean $CO_2$ after they have produced urea. The location of a plant depends essentially on the availability of good inexpensive $CO_2$ gas (99% pure) in large quantities, and access to an inexpensive supply of electricity for liquefaction. As a result, the tendency is to have a limited number of large plants but these are not necessarily in the right location for the best distribution network. The smallest manufacturing plant now has a 100 metric tons/day capacity. All plants of lesser importance have now been closed and new plants are now built with a 300 metric tons/day capacity. A list of plants with their name plate capacity per day will give an idea of their poor distribution in Canada.

| LIQUID CARBONIC | | LIQUID AIR - CARDOX | |
|---|---|---|---|
| Montreal, (Quebec) | 200 | Montreal (Quebec) | 150 |
| Maitland, (Ontario) | 275 | Niagara Falls, (Ontario) | 100 |
| Clarkson, (Ontario) | 100 | | |
| Courtright, (Ontario) | 650 | Courtright, (Ontario) | 300 |
| Brandon, (Manitoba) | 100 | Calgary, (Alberta) | 150 |
| Fort Saskatchewan, (Alberta) | 320 | Medecine Hat, (Alberta) | 300 |
| | 1645 | | 1000 |

Of this total capacity, only about 350,000 metric tons per year are sold and about 50% of that is exported to the US where duties are only 4%. This means that the consumption in Canada is less than 200,000 metric tons and 90% of that is sold during three months of the year. (By comparison, the consumption of liquid $CO_2$ in the United States is 15 times greater, or 3,000,000 metric tons.) Most sales are made in the spring to the fishing industry, and during the end of the summer months for the food processing industry, during these periods, exports to the United States are cut down as much as possible to meet the Canadian demand. Every so often, there might even be a shortage in a certain area and liquid $CO_2$ has to be transported from longer distances.

To compensate for this manufacturing over-centralization, $CO_2$ manufacturers open depots wherever they consider this justified. These depots are usually beside a railroad siding, as bulk train transport is much cheaper than road transport and quantities transported are much larger (75 tons/per tank). There are over 100 cars supplying this traffic in Canada.

For example, in the East there are the following depots:

60 tons in St John, Newfoundland
230 tons in Halifax, Nova Scotia
400 tons in Moncton, New Brunswick
150 tons in New Richmond, Quebec
250 tons in Quebec City
200 tons in Varenne, Quebec

Liquid $CO_2$ is distributed from these depots and the manufacturing plants by tanker trucks (up to 35 tons per load) to the various users (their storage tanks vary from a few to 50 tons). A large user will buy over 1500 tons per year but few take at least 100 tons/per month, 12 months of the year.

It is obvious that if liquid $CO_2$ were used for refrigerated transport, the volume consumed in Canada would increase considerably and this consumption would not be only during one or two months in summer. This is important since, at present, the price structure of this industry is very complex. In early spring and the fall, and even more so in the winter, there is a very large production over-capacity, and excellent prices can be negociated, especially in the Prairies. In the summer however, this situation changes, and price is dictated by the law of supply and demand. A steady customer can negotiate a much better price than an occasional user. (A price of $60 - $65 per ton for a distance of 50 km from Montreal is considered a good price for a big customer. During the summer, a big occasional customer might have to pay $80-$100/ton in Montreal, and more if he is far from a production center).

The other factor affecting price is the distance from a manufacturing plant. On average, there will be a $2 charge per km added to the delivery price, outside a 50 km radius, when using a large delivery truck (27 to 35 tons). This represents an increase of about $7 per ton for every 100 km away from the manufacturing plant, for full loads. When dealing in small quantities, this additional charge can easily double.

## 1.3 Cryogenic $CO_2$ Refrigeration

Traditional Cryogenic Refrigeration consists of converting liquid $CO_2$ kept in a pressure vessel at rather low temperatures, about -20°C (-4°F), and relatively high pressure, about 18 bars (270 psi), into dry snow and gas at -78.5°C (-109°F), by releasing it into the atmosphere. This operation generates between 310 and 330 kJ of refrigeration per kilo of liquid $CO_2$ released (135 and 145 Btu per pound), depending on the pressure of the liquid. About 45 kJ (20 Btu) are derived from the quick warming of the gas from -78.5°C (-109°F) to ambient temperature; the balance, 265 to 285 kJ (115 to 125 Btu) is found stored in the dry snow. One cubic meter at -16°C of liquid $CO_2$ weighs 1010 kg and is consequently equivalent to 313, 100 kJ (or one cubic foot of liquid $CO_2$ weighs about 63 pounds and is consequently equivalent to about 8500 Btu.)

If this dry snow is in small quantities and in powder form, it will very quickly sublimate and immediately release these kilojoules or Btu's. If, on the contrary, it is compressed into blocks or left to accumulate in large tanks, the release of the kilojoule/Btu will be slowed down as only the exposed part of the dry snow will progressively convert to gas by sublimation. The dry snow, as it sublimates, will release 571 kJ/kg (246 Btu/lb).

These characteristics are used by all the various cryogenic systems which use liquid $CO_2$ by injection to create refrigeration. If the injections are short and made inside a closed and tight space, all the energy contained in a kilogramme of liquid $CO_2$ will be used to absorb the heat infiltration or the heat to be removed. The additional pressure created by the gas will be small compared to the volume of the space to be refrigerated and the system will be very energy-efficient.

But if the injections are long or continous to create a "dump" of dry snow, the quantity of gas generated will be so great that the pressure inside the space to be refrigerated will rise so high, and so fast, that a very large part of the gas will have to be ejected out of the closed area as soon as it is generated to avoid busting the walls and before the kJ/Btu can absorb any heat. This will result in a rather high waste of kJ/Btu as the actual kJ/Btu finally used for refrigeration will be no more than the 265 kJ/kg (115 Btu per pound) of liquid $CO_2$ used, to be converted into dry snow, generating ultimately 571 kJ/kg (246 Btu per pound) when it sublimates at -78.5°C (-109°F). This means that it takes at least 2.2 tons of liquid $CO_2$ to generate 1 ton of usable dry ice. This is what happens when manufacturing dry ice or when dumping a large load of dry snow in a tank to be progressively sublimated, as it is currently done on the Burlington Railroad Cars in the United States.

There is another method of using liquid $CO_2$ for Cryogenic Refrigeration, and this is the approach which has essentially been used to develop the system presented in this research. The approach consists in utilizing the latent heat of vaporization of $CO_2$, when changing from liquid to gas inside a closed container. The latent heat of vaporization is the amount of energy necessary to convert one kilo of product from the liquid state to the gaseous state at a given pressure and temperature. For example, one kilogram of liquid $CO_2$ is vaporized at 20 bars (300 psi) and -17°C by adding 276 kJ/kg. The latent heat of vaporization will increase as the temperature and pressure decrease so, at -30°C (-20°F) and 13 bars it will be 300 kJ/kg, but at 0°C (32°F) and 33 bars it will be only 235 kJ/kg.

This property of $CO_2$ is the foundation of the Coldsink technology patented by Concool in the development of the AFFCAR Cryogenic Rail Car. Concool has obtained several patents protecting its development in the field. Fridev has made an agreement with Concool for the use of these patents in making further developments in the Cryogenic field.

Both the injection technique and the vaporization technique have been fully researched and tested in the development of the proposed $CO_2$ refrigeration system.

### 1.3.1 Injection Technique

It is obvious that this technique is the simplest way to use Cryogenic $CO_2$ Refrigeration. It is generally used for applications in the frozen food industry, and particularly the operation of freezing tunnels, as it permits quick and intense refrigeration.

For the transport industry, the injection technique was pioneered in Canada by Porta-Cold of Liquid Carbonic Co. early in the 1970's. It is still being used successfully in Canada for the transport of frozen meat from Halifax to Montreal and Toronto by the Columbus line, using the Thermotrol clip-on which had been developed by Galt Equipment around 1978.

In this method, liquid $CO_2$ is injected with a nozzle inside the cargo area when required. This liquid converts to dry snow, which in turn sublimates into gas and creates the required cold temperature. The injections start as soon as the temperature drops below a set point, and stop when the right temperature is attained. The injections are short and pulsed, to avoid over-shooting and to insure accurate, even temperature. The system works very well with frozen foods, as the turbulence created by the injection permits a complete cooling of the total load. Tests with fresh produce have indicated that it is difficult to maintain an even temperature inside the cargo, as the dry snow $CO_2$ is very cold and the sublimation process takes place mostly on top of the load. More important, many products, such as leafy vegetables, are directly affected by an excess concentration of $CO_2$, which stops the "breathing" process of the product. Finally, the high concentration of $CO_2$ gas inside the cargo area is objectionable as it affects the respiration of the workers who unload the products - unless they wait long enough for the vapors to dissipate. The reserve of liquid $CO_2$ required to operate the system is contained inside an insulated pressure vessel tank, outside the transport vehicle.

### 1.3.2 Vaporization Technique

In this technology, some liquid $CO_2$ at a given pressure is enclosed in a closed piping system exposed to the heat to be absorbed. When this heat comes in contact with the cold piping system, it is absorbed by the liquid, and part of the liquid $CO_2$ converts to gas.

Since the volume of a unit of gas is much greater than the volume of a unit of liquid (25 to 1), the pressure inside the closed piping system progressively increases. When the pressure reaches a pre-set level, a vent is opened which releases part of the gas outside the piping system. The pressure immediately decreases inside the system and the vent is closed again when the pressure has been brought back to the original pressure. By that time, the temperature of the liquid $CO_2$ has returned to its original level

and the system is ready to absorb more heat for a new cycle. The closed piping-system is called a Coldsink. By adjusting the pressure in the Coldsink, and by developing appropriate heat transfer plates to facilitate the transfer of heat to the liquid $CO_2$, it is possible to regulate the temperature of the surrounding area very accurately and with a minimum of controls.

If the temperature to be maintained is very low, then the pressure of the liquid $CO_2$ in the Coldsink is brought to a very low level; vice versa, if the temperature to be maintained is high, the pressure will be raised. In every case, the temperature of the Coldsink has to be lower than the temperature to be maintained to generate heat absorption. How much lower will depend on the amount of heat to be absorbed. If the heat transfer is high, the spread will be high; if the heat transfer is small, the spread will be much reduced. The consumption of liquid $CO_2$ is in direct relation to the heat to be absorbed: if the amount of heat is considerable, then the consumption is large. If, on the contrary, the amount of heat to be absorbed is limited, the consumption of liquid $CO_2$ will be small. In all cases, the temperature will be precisely maintained inside the cargo area.

It is the understanding of these two techniques and the proper utilization of liquid $CO_2$ inside the system which constitute the technical research of this project, proving that Cryogenic $CO_2$ Rrefrigeration can be a valid alternative to Mechanical Refrigeration.

## 1.4 Manufacturing Standards, Laws and Regulations

Any Carbon Dioxide system must be designed to safely contain the pressures involved and must conform with all regulations governing transportation.

The first regulation concerns the $CO_2$ Reserve tank used to store the liquid $CO_2$ needed to operate the system. It is a pressure vessel, and as such, it must comply with the ASME standard, "boiler and pressure vessel code 1986" section VIII, division I, as well as with code UCF-56 of the American Society of Mechanical Engineers and to CTC specification 51 of the Canadian Transport Commission. For the piping system, CSA standard B51-M1981 "Code for the construction and inspection of boilers and pressure vessels" applies. As it is installed on a vehicle, it must also comply with the codes for the transportation of dangerous goods.

In this case, it must comply with CSA standard B620-1987 and CSA standard B622-1987 which apply more precisely to class 2 products for transportation by road.

Naturally, before being manufactured, approval of the plans and specifications of the pressure vessel, plus approval of a quality- control program must be secured from the Canadian and Quebec governments.

Two aspects of the regulations are particularly important for the development of a new system:

- Reserve tanks should not carry more than 500 kg (1100 pounds) per tank to be allowed to enter tunnels without restriction.

- If the diameter of a cylinder is 15 cm (6") or less, or if the volume of a tank is less than .04 $m^3$ (1.5 $f^3$) the equipment is not considered a pressure vessel, and, consequently, it is not necessary to have an inspection and registration every five years as for a standard pressure vessel.

This latter point is very important if the tank is designed to become an intrinsic part of the vehicle, since access for regular inspection might then become difficult.

## 2. CRYOGENIC CO2 REFRIGERATION VERSUS MECHANICAL REFRIGERATION

As Mechanical Refrigeration is the standard in the food industry, it is important to understand both types of refrigeration in order to evaluate the respective advantages of each approach.

### 2.1 Functioning of a Mechanical Refrigeration system

Mechanical refrigeration is obtained by circulating a cold liquid refrigerant inside a closed piping system. As warm air comes into contact with the piping system, inside a compact heat exchanger, it becomes much colder, as any existing heat in the air is quickly absorbed by the liquid refrigerant. While it absorbs heat, the liquid refrigerant turns to warm gas. This warm gas in turn has to be condensed and compressed, in order for the refrigerant to become a cold liquid again, ready for a new liquid circulation cycle.

After the ambient heat has been removed inside the heat exchanger, the cold air is then blown into the area to be refrigerated with a powerful blower. This cold draft picks up whatever heat is inside the storage area and brings it back to the intake of the heat exchanger, to be absorbed again by the cold liquid refrigerant.

The capacity of the blower has to be selected to ensure that an adequate draft is created inside the storage area, to permit the return of the warm air to the heat exchanger. The heat absorption capability of the heat exchanger has to be very efficient to ensure that the heat of the air will be absorbed quickly, during the short time the air circulates inside the heat exchanger. This result is obtained by using a very tight network of finned piping which must be calibrated according to the type of heat absorption expected. Similarly, the compressor, which will turn the warm gas back into a cold refrigerant, has to be calibrated according to the amount of liquid to be compressed, and the type of refrigerant to be compressed. Several types of refrigerant are used for Mechanical Refrigeration systems. Ammonia has been used extensively for large and fixed installations. Lately, the trend has been to replace it by a CFC 12 called Freon which is easier to use. Freon comes in different grades, depending on the amount of refrigeration required, and each one has its own characteristics.

For cooling, Freon ®12 is preferred. For subfreezing, the choice is Freon ®502. Freons ®22 and ®500 can be used with success for temperatures between these two. However, a Mechanical Refrigeration system will only be able to achieve what its refrigerant can do. For the transportation industry, this represents a big problem since many types of products with different refrigeration needs are transported and the refrigerant does not necessarily have the required flexibility. The compressor is designed for only one type of refrigerant.

Finally, the source of power which operates the compressor is an important part of the system. In fixed operations, a good electric motor, appropriately sized, is obviously the best and cheapest way to operate the system. A diesel motor is used in most cases for transportation system. This is where the choice of the diesel and compressor configuration might become a real problem, since a motor large enough to operate the system in the warmest months of the year becomes a cumbersome piece of equipment when the power demand is small, as during the spring and fall, or when used in a different capacity, to operate the heating system during the winter months. Manufacturers of Mechanical Refrigeration units have struggled with these various constraints for the last fifty years, with more or less success, the result being that some fairly good units are now available on the market. However, whether these units are always suitable for every application, as their manufacturers would have us believe, is another matter.

### 2.1.1 The heat exchanger

If the heat absorption capacity of the heat exchangers is very high, this means that the difference in temperature between the refrigerant and the room to be refrigerated has to be quite small, or the cooling effect will be too strong for the specific application. This will immediately affect the choice of refrigerant to be used in each case. If the heat absorption capacity is limited, there might be a problem when a lot of cooling is required, unless the type of Freon used permits this additional cooling load. Also, depending on the application, the number of fins per centimeter in the heat exchangers might be adequate for cooling, but not necessarily for freezing, since they will be covered with ice, and will require frequent defrosting cycles.

### 2.1.2 The blower

If the Mechanical Unit operates in a fixed location, and has a predetermined job to perform, it is relatively easy to select the right type of blower, to guarantee the proper circulation of cold air inside the room, and the proper intensity of the airstream. For transport vehicles, the necessary ventilation is very difficult to achieve, particulary now that very long transport units are used (up to 16 meters or 52'long). To reach the back end of the vehicle and ensure the return of air to the nose, an extremely powerful air flow is required. However, this flow is very difficult to control when very little air circulation is required to ensure proper cooling. Manufacturers are using all types of ducting systems to try to direct the air into the right places; they are using speed reducers for the blower; and they are recommending special designs for the trailers. But the problem remains that, in most cases, the intensity of the air flow is such that it dessicates any product which is exposed to it for any length of time. Also, too often, the air flow has a tendency to go around in circles, above the load, putting a lot of cold air in a specific area of the trailer without infiltrating the rest of the cargo.

### 2.1.3 The compressor and Freon refrigerant

Choosing the compressor and Freon refrigerant is obviously a major task, as the compressor is directly related to the type of Freon used in the system. Once the decision is made, it is not recommended, or even possible sometimes, to change the application of the equipment, as the gas pressures are so different. The Freon chosen is either good for cooling, or for freezing; it cannot do both well. Some manufacturers are offering kits to make the conversion, but it is questionable how dependable these kits are when used on hermetic or semi-hermetic compressors. This issue has become more complicated with the CFC controversy concerning the depletion of the ozone layer. If, as is suggested, Freon production must be considerably reduced in the coming years, how will it be possible to adapt existing compressors to new types of refrigerant since they will not necessarily have the same characteristics as the Freons currently used?. Now, if a compressor is built to operate with Freon ®12, it cannot be used to operate with ®502 unless it is converted. Consequently, if the trailer is equipped with this type of compressor, it cannot safely transport frozen foods, as ®12 does not have the refrigerant capacity to do the job properly. If the new refrigerant developed to replace ®12 has characteristics similar to the existing ®502, what choices will be available? Convertion of the trailer to transport frozen foods is unlikely as the other components of the system are not calibrated for this purpose. It might be possible to change the compressor providing the diesel has the proper characteristics to handle a different compressor. It can be seen that the changeover from Freon to alternate refrigerants may create a big problem for transporters in the near future.

### 2.1.4 The diesel motor

Currently, the new Mechanical Refrigeration systems are very powerful in order to ensure proper cooling of the huge vehicles manufactured. The diesel unit needed to operate the system during the summer months is necessarily grossly oversized for the rest of the year. Many techniques have been developed to slow down the consumption of diesel fuel, and suggestions are sometimes made to install a stop-and-go system which will completely stop the diesel when cooling or heating is not needed. But then, how is ventilation provided if the motor is not running? Will the motor start in winter, after it has been sitting idle in the cold? All these questions should be addressed before attempting to adapt a huge motor to a small job.

## 2.2 Advantages of Mechanical over Cryogenic Refrigeration

### 2.2.1 Constant very high temperatures

When a Mechanical Refrigeration system is operating continously at full capacity, it is very efficient and inexpensive, since it is possible to calibrate the unit to match the specific refrigeration needs. If a trailer is always operating in a very hot

environment, it would be useless to even consider the use of Cryogenic Refrigeration, as the consistent high consumption of $CO_2$ would make it very expensive, and the weight of a very large reserve of $CO_2$ fuel would overburden the vehicle.

2.2.2 Very irregular transport patterns

Diesel fuel is available everywhere; liquid $CO_2$ is not, and will not be, for the forseeable future. Consequently, if the transport vehicle is expected to be used in different directions without any stable pattern of traffic, it is useless to even consider the use of Cryogenic $CO_2$ refrigeration. This would be, for example, the case in the "Gypsy" type of transportation. But this does not mean that public transporters cannot consider using $CO_2$ refrigeration. First, because most perishable products transported follow a definite traffic pattern. Second, because of the fact that Cryogenic systems can be successfully used for every temperature. It becomes, for the public transporter, a matter of selecting, between the varied equipment available, which one is best adapted to the job, in exactly the same way that he has to decide between chilling and freezing units to transport specific products to different places.

2.2.3 Products transported at very high temperatures

For these products, Mechanical Refrigeration is particularly well adapted since the products are not directly affected by high ventilation and the refrigeration units equipped with R12 can operate at high temperature levels with a powerful built-in heating system. This is not an application for Cryogenic $CO_2$ Refrigeration.

Cryogenic systems are most efficient when the liquid $CO_2$ is used at pressures of 20 bars (300 psi) or lower. They can operate at higher pressures, but the number of kilojoules obtained from a kilogram of $CO_2$ decreases with pressure increases; and the cost of manufacturing increases if the piping has to be built to accept very high pressures. Furthermore, the heating system which has to be added to the Cryogenic system will make demands on the $CO_2$ supply, if the heating system cannot be connected to an outside source of electricity, such as the alternator of the tractor. Heating a cargo area so that the product will not freeze when transported at 0°C is one thing, but keeping the cargo at 15°C when it is -30°C outside is something else. Any time a product has to be transported regularly at a temperature higher than 10°C, Mechanical Refrigeration should be prefered to Cryogenic $CO_2$ Refrigeration.

## 2.3 Advantages of Cryogenic over Mechanical Refrigeration

2.3.1 Irregular, extremely high temperature

Cryogenic Refrigeration capacity is based solely on the amount of liquid $CO_2$ injected or vaporized during a given period of time, at the rate of 275 kilojoulesper kilogram of liquid $CO_2$. Consequently

the system can adapt automatically to extreme changes of outside temperature without changing any part of the system. This means that, during the few days of summer when temperatures are torrid, the system, even if it consumes a lot of $CO_2$, will be able to meet the task by keeping the pressure of $CO_2$ very low. Then, when the temperature is milder, the same system will be used but the consumption of liquid $CO_2$ will go down to practically nothing as outside temperatures get closer to the inside temperature. Since the heating system operates on the same principle, the complete system is adapted to widely fluctuating temperatures without having to be burdened with equipment which is not needed most of the time.

### 2.3.2 Flexibility in Refrigeration level

The same Cryogenic equipment can be used equally for transporting perishable products at any temperature level, from -30°C to 5°C, with extremely accurate temperature stability. If products are affected by high $CO_2$ concentrations, the system can be designed so that the $CO_2$ vapor concentration is never in excess of 3% per volume, or will be completely eliminated if quick pre-cooling or re-cooling is not required.

### 2.3.3 Very regular transport patterns

If the pattern of transport of a specific perishable product is such that the traffic absorbs the totality of the refrigerated vehicle activity, then it becomes possible to tailor-make the Cryogenic $CO_2$ Refrigeration system to the most efficient performance, in terms of capital and operation cost, with minimal maintenance, and minimal quantities of reserve $CO_2$ fuel transported. This is particularly true for a private fleet which would own its own liquid $CO_2$ storage tanks, since in some cases they could already use liquid $CO_2$ for their own processing. The company would then considerably increase its consumption of $CO_2$, and consequently its purchasing power.

### 2.3.4 Products which suffer from excess ventilation and/or benefit from $CO_2$ environment

Some products, such as fresh meat or fish, can benefit tremendously from a certain concentration of $CO_2$ in the atmosphere which reduces bacterial growth, and, at the same time, completely eliminates excessive ventilation which has a tendency to dessicate the product. This aspect of transportation will be discussed in greater detail later in this report.

## 3. CONSIDERATIONS FOR GOOD REGRIGERATED TRANSPORT

### 3.1 Environmental Conditions

#### 3.1.1 Temperature requirements of products transported

Each perishable product has an optimum temperature range during transport. Every effort should be made to maintain this temperature, determined after much research and testing. The optimum temperature may be the result of many conflicting specifications and compromises. The best temperature to stop the growth of bacteria is not necessarily the best temperature to ensure freshness or the bloom of the product, or preserve its color and flavor. Also, some processes might require temperatures which are very exacting and not necessarily compatible with the overall quality of the product. Even packaging material can be adversely affected by temperatures which are recommended for a specific product. Before attempting to transport a perishable product, every possible effort should be made to identify the optimum temperature suggested.

Some products are more sensitive than others to temperature change, and consequently, the type of refrigeration used for their transport should take into consideration this factor, particularily if the transport is to be repetitive. Most products are inert when they are transported, and thus, if the temperature is correct at the time of loading, it is just a matter of maintaining the temperature without fluctuation. But some products, like fruit and vegetables, are still "alive", and they generate their own heat during transportation. It becomes much more delicate to maintain the temperature at a set point, if the product temperature fluctuates by itself, and it becomes even more delicate when the product has to be transported at a temperature close to the freezing point.

As a general rule, it is not suggested to mix on the same load, products which do not have exactly the same temperature requirements. It is possible to classify products by group of compatibility, to simplify the job of selecting the optimum temperature for good refrigerated transport, whenever different products have to be loaded on the same vehicle.

Mechanical Refrigeration units used for transport are built to answer the needs of a specific range of temperature. It is unwise to try to do all types of transport with only one type of mechanical refrigeration unit. It is wrong to believe that by using an oversized unit it will be possible to do the right job for every type of product. Contrary to a widely - help opinion Mechanical units are not versatile at all, and they should, in most cases, be tailor-made for the type of product they are intended to transport.

If the unit uses R12 Freon, it should not be expected to transport frozen foods which require Freon R22 or R502. If the unit is built for a big trailer it should not be used on a pop trailer, as the ventilation would be much too strong.

### 3.1.2 Climatic environment for transport

Those afortunate enough to live in very temperate climates with little fluctuation, in temperature have relatively simple needs in regard to local refrigerated transport. In some areas of the United States, for example, the temperature never goes below freezing so there is no need for a heating system. But when people are concerned with long-haul transport the problem is quite different.

A product might have to travel under very different conditions from its area of origin. For example, the outside temperature might be 40°C when goods leave Arizona, but the trailer might have to make delivery in Calgary at -30°C. In this case, the same vehicle and refrigeration unit must cope with both situations, and maintain the products at the same temperature, regardless of the outside temperature. The manufacturers of refrigeration units know the average temperatures that they can expect, but they must always expect the worse, and be ready to cope with extreme fluctuations.

## 3.2 The importance of Dt in Refrigerated Transport

Dt is the difference between the ambient outside temperature and the temperature to be maintained inside the cargo box (according to the product transported). When selecting a refrigeration unit, it is very important to make sure that the unit will have enough capacity to operate in the most extreme DT conditions to be faced during any one transport. The equipment must also be able to pre-cool the cargo box in a reasonable amount of time before loading the trailer, or sharp changes in temperature for the cargo can be expected.

### 3.2.1 Maximum extreme Dt's

In some areas of the North American continent, such as in Arizona, extremely high temperatures can be faced during a few hours of the day and a few days of the summer (eg. over 60°C or 140°F). However it is not unusual for the temperature to reach 50°C (120°F). A truck operating regularly in the southern region of the United States must be able to meet this temperature.

In Canada, the highest temperatures during the summer seldom exceed 38°C (100°F) and this only for a few hours and a few days. Therefore, it is not necessary to use a higher temperature to calculate the required capacity of a refrigeration unit operating in Canada. Meanwhile, the recommended temperatures to be maintained inside the cargo box will vary, depending on the products transported.

- Chilled produce will be maintained between:
  -1° and +2°C (30° and + 35°F)
- Frozen food will be maintained between:
  -20° and -18°C (-5° and 0°F)
- Sub-cooled products, such as ice cream and fish, are maintained at:
  -30°C (-20°F)

Consequently, in Canada, if the product is to be handled adequately, the extreme Dt to be used for a mechanical refrigeration unit will be :

36°C (65°F) for chilled products
54°C (100°F) for frozen foods
66°C (120°F) for subcooled products

But if the vehicle has to travel from Arizona to Canada the extreme Dt becomes:

60°C (105°F) for chilled products
78°C (140°F) for frozen foods
90°C (160°F) for subcooled products

Taken separately, the actual Dt can fluctuate tremendously from morning to night, from January to July and from Arizona to Quebec City.

A good refrigeration system must be able to cope with the extremes, but unfortunately this is where it becomes very difficult for a Mechanical Refrigeration unit to operate. The temperature extremes force the manufacturers to oversize their equipment, with the result that most of the time the equipment has to work in a situation of over-capacity. This is obviously not very efficient mechanically, energetically, or financially speaking.

### 3.2.2 How mechanical units adapt to the fluctuations in Dt in relation with the U factor of the box

A Mechanical Refrigeration unit is not as flexible as its manufacturer would like to believe. As the Dt increases, the cooling capacity of the unit decreases. For example, the largest Thermoking or Carrier units will develop, at 38°C (100°F) ambient temperature, the following capacity :

| Dt | | Return air to Evaporator | | kJ/h | Btu/h |
|---|---|---|---|---|---|
| 36°C | (65°F) | 1.7°C | (35°F) | 45,900 | 43,500 |
| 54°C | (100°F) | -17.8°C | (0°F) | 22,150 | 21,000 |
| 66°C | (120°F) | -29°C | (-20°F) | 11,600 | 11,000 |

Consequently, if the transporter selects a unit capable of adequately transporting sub-cooled products during the summer, this piece of equipment will, most likely, be very oversized for any other type of refrigerated transport.

At 38°C (100°F) ambient temperature, if the unit develops 11,600 kJ/h (11,000 Btu/h) at -30°C (-20°F) or a Dt of 66°C (120°F), a trailer with a U Factor of 170 kJ/h/°C (90 Btu/h/°F) should be satisfactory (170 x 66 = 11,220 kJ or 90 X 120 = 10,800 Btu).

However, with such a trailer, for the same ambient temperature:
9500 kJ/h or 9000 Btu/h are required at -18°C(0°F), not 22,150kJ/h or 21,000 Btu/h
6200 kJ/h or 5850 Btu/h are required at 2°C(35°F), not 45,900 kJ/h or 43,500 Btu/h

Conversely, if the transporter selects a unit capable of adequately transporting chilled products during the summer, this piece of equipment will be totally unacceptable for frozen or sub-cooled products in the summer.

At 38°C (100°F) ambient temperature, if the unit develops 14,800 kJ/h at 1.7°C (35°F) or a Dt of 36°C (65°F), a trailer with a U Factor of 380 kJ/h/°C could do the job (380 X 36 = 13,680 kJ) However, with such a trailer, for the same ambient temperature, the requirements would be 21,000 kJ/h for frozen products instead of the 7,400 kJ/h that it can develop; or 25,300 kJ/h for sub-cooled products instead of the 4,200 kJ/h offered.

This type of risk and lack of flexibility are not desirable for the transporter; consequently, they will have a tendency to always purchase the biggest unit available for long-haul transport, so that they do not have to worry about insufficient cooling capacity. As a result, because the diesel, the compressor, the condenser and evaporators are oversized, most of the time the equipment works way under capacity, but it can never be stopped as hot spots would develop. During this time, the consumption of fuel and wear of parts goes on, even if it is at a reduced rate.

### 3.2.3 High, Low and Mean temperatures per Day, Month, Year

Contrary to working with a mechanical refrigeration system, when working with a cryogenic system the highest possible temperature is not the relevant factor to consider, as the system can adapt itself to any extremely high temperature immediately. The most important temperature to know is the mean temperature to be expected during the day, the week, the month or the year. This temperature establishes the Dt to be taken into consideration while determining the estimated consumption of $CO_2$, and, consequently, the size of the $CO_2$ Reserve to be installed.

Obviously, a minimum safety margin must be preserved for those occasions when extreme conditions are encountered. Meteorological offices keep detailed records and analyses of high, low and mean temperatures for each city and will develop average high, low and mean temperatures for any given day, week or month of the year. Naturally, when using these mean temperatures, the most likely locations and roads used by the trailer must be taken into consideration when determining the anticipated mean temperature

and consequent mean Dt to be used.

### 3.3 The Transport Regulations

Another problem for the long-haul transport industry is the number of transport regulations which vary from province to province, or state to state. There are various limits in the maximum weight allowed by axle, in the maximum weight of a vehicule, in the configuration of the vehicule, and in the overall size of a vehicle. To avoid problems on the road, a tractor-trailer rig should be below every one of the limits that might be faced; this is can be very uneconomical depending on the type of product that is transported. Some products will reach the volume limit before reaching the weight limit ("cube" before they "weight") while others do the opposite ("weight" before they "cube"). Depending on the product transported, the rig will be too heavy or too small.

There is presently an attempt to standardize these various regulations but, until this is done, the only way to have efficient transportation is to have a specialized piece of equipment tailor-made to the specific regulations affecting the transport of a specific product.

### 3.4 Appropriate isotherm vehicles

One of the major factors which affects good refrigerated transport is the choice and the construction of the insulated box. The manufacturers of refrigeration units are especially to blame for the existing situation. Because they have to manufacture refrigeration units which are able to cope with extreme conditions (even if these seldom happen) they are promoting the idea that their units are so powerful that they hardly need an insulated vehicle to work properly. They are convincing users that any insulation will do and that they should not spend the money to get a good isotherm vehicle. They imply that the only important thing is to get a very large box where they can load two pallets one next to the other. They do not mention the fact that their huge units are grossly oversized and they encourage the transporter to use a poorly insulated vehicle 365 days a year to make use of a refrigeration capacity which has been designed to face 10 bad days a year. Finally, they convince their customers that their refrigeration units are adapted to these huge trailers when, in fact, this assertion is questionable.

Research on refrigerated transport from 10 to 20 years ago, was very concerned with the quality of insulation, construction techniques and the design of the cargo box. Experiments proved, time after time, that a good box was good insurance for efficient refrigerated transport. The quality of the insulation used to limit heat transfer is expressed by an R factor which varies, depending on the insulating K factor of the material and the thickness of the insulation used. To this R factor must be added

all the other potential factors which might affect the quality of the box, such as: reflective white color against sun rays, unicoque construction to limit air leakage, tightness of the door, etc.

The overall quality of a box is measured by a U factor which includes the resistance of the insulation to heat transfer, air leakage, sun reflection, ram effect, etc. The U factor is naturally affected by the overall size of the insulated box. An excellent 48' box might have a U factor equal to 50 Btu/h/°F which correspond 95 kJ/h/°C. This is what is called a "Supertherm", but it is rather unusual. Most good boxes will rate around 225 kJ/h/°C or 120 Btu/h/°F, all heat transfers included.

Unfortunately, in the last few years, to gain some cubic space, a new type of box, "the thin wall" has been promoted on the market. These boxes have, most of the time, very questionable U factors because they are calculated after putting a very high level of insulation in the roof but practically nothing in the sides (max 6 cm or 2 1/2" insulation). These boxes might, in effect, have a U value of up to 340 kJ/h/°C (180 Btu/h/°F) or even worse. Also, some old trailers might have insulation which has deteriorated completely and might reach way above 380 kJ/h/°C (200 Btu/h/°F). Since the refrigeration units are so oversized and have much more capacity than needed, most of the time they could almost protect perishables without any insulation at all. It was therefore natural that this "thin-wall" trend would be encouraged by the refrigeration unit manufacturers, who found a way of covering their inadequacies in adjusting their machines to the right refrigeration load, by recommending that their clients cut down on the quality and insulation of their trailers, (and consequently the cost), because they could compensate for the lack of insulation by using their "bigger and bigger" units with very high cooling capabilities. This might work as long as the unit works. When there is a breakdown, then it is a catastrophe. In no time at all, the heat penetrates the cargo box (or escapes in the winter) and the whole load is lost, with no possibility of salvage.

In the case of Cryogenic $CO_2$ Refrigeration, the refrigeration effort is directly related to the actual need, consequently, good insulation and construction of the cargo box are mandatory, as it is the only way the cost of $CO_2$, under very high temperatures, can be kept in check. This also guarantees very inexpensive and dependable refrigerated transportation throughout the year.

### 3.4.1 Insulation Material

Consequently, it is felt that a vehicle is not isothermic unless it is properly insulated. A minimum thickness of insulation is required all around, but the most important parts remain the roof and the floor. The roof is where the strongest sun rays hit the van. Insulation should be at least 10cm (4") or preferably 15cm (6") of good polyurethane. The floor is the most difficult part to refrigerate properly and since a lot of heat is generated by

the road, it should be protected with at least 10cm (4") of polyurethane.

The front and the back doors should be insulated with at least 10cm (4") of insulation, and should be very tight, as they are directly affected by the Venturi effect.

Manufacturers most often compromise on the insulation of the sides so that they can offer a trailer with more than 240cm (96") inside dimension from wall to wall, (to fit two 120cm (48") pallettes across). In fact the sides should have insulation of a thickness greater than 6cm (2 1/2"). A new German technology claims to be able to insulate trailers properly with less than 6cm. This should be verified. If true, this is excellent, but meanwhile it will not help all the existing poorly-built trailers. It is our opinion that a trailer which has an overall U factor higher than 280 kJ/h/°C (150 Btu/h/°F) should not be used for transporting perishable goods, even if a Cryogenic $CO_2$ refrigeration system could handle very poorly-insulated vehicles.

### 3.4.2 Material for the Body

Many types of material are available for insulated trailers: steel, aluminium, FRP, fiberglass, etc. Because of the additional weight required by the insulation and the refrigeration unit, aluminium or fiberglass are preferred because they permit a reduction in the overall weight of the trailer. This is imperative, considering the multiple weight limitations on the Canadian and American roads.

### 3.4.3 Construction Techniques

Again, the lightest type of construction should be encouraged to cut down on the weight of insulated vehicles. Monocoque construction, without a base frame, can be made as strong as any standard construction. New technologies in bonding materials might also be taken under consideration.

### 3.4.4 Air infiltration

This is a factor which is very often overlooked. A tight trailer will protect perishable products as well as good insulation. The minute there is a crack in the body, the air infiltration will distort any effort made to ensure adequate ventilation in the cargo space, and equalization of temperatures. Door gaskets, for example, are the source of constant problems.

### 3.4.5 Ventilation versus Air Circulation and Air turbulence

This is one thing that manufacturers of Mechanical Refrigeration units promote actively, because it is needed it to operate the system. Without strong ventilation, their systems would be absolutely useless. However, it is not strong ventilation, as much as good air circulation, that is needed inside a trailer. It is not the amount of air which is important, it is how it is distributed inside the box which counts. Since the trend is to

increasingly larger transport trailers, for example:

16 meters (52') Long, 260 cm (102") Wide, 4.2 meters (13'.6") High, the air flow inside the box becomes a very big problem for the mechanical refrigeration unit, as the huge size of the box creates static pressures which limit proper circulation of the air.

It is fairly common now for manufacturers to develop as high as 4 air changes per minute in the box. This is extremely high, and detrimental to most products which dessiccate very quickly. The air flow, on the contrary, must never be stopped, to avoid temperature fluctuations and damage to the merchandise, unless this merchandise is absolutely not affected by high temperature fluctuation (which is rare with perishable food products).

Many studies have been done on this subject and many systems have been developed to improve the air circulation, such as reverse flow, jacketed walls, and grooved sides. Still, the air circulation is not adequate. It is our considered opinion that a good air turbulence is preferable to a powerful air stream for good transport refrigeration. This is why the concept of a compact heat exchanger in the nose of the trailer has been replaced by that of a Coldsink in the ceiling, an alternative that the Mechanical Refrigeration system cannot use.

In any system, the floor is the hardest part of the trailer to ventilate properly, particularly if the shippers use slips rather than pallettes. With the new 50' trailers, the air is easily trapped inside the floor tracks and any obstruction can block the air circulation altogether. Up to now, lateral air circulation in the floor has never been seriously developed because it does not represent any advantage for Mechanical Refrigeration. However, it should be promoted more actively, as it is just as important as longitudinal air circulation to ensure proper air flow alongside floor and the walls.

### 3.4.6 Doors

Needless to say, the construction of the back door is of prime importance to ensure an adequate isothermic vehicle. Not only should the door be tight, but it should facilitate the circulation of air in the back of the trailer where it is extremely difficult to keep good refrigeration, particularily when the doors are opened often.

## 3.5 Characteristics of a good refrigeration system

### 3.5.1 Ability to maintain temperatures

The ability of the refrigeration system to maintain the temperature inside the cargo space at a predetermined level, regardless of outside atmospheric conditions, without human intervention or adjustment, is of prime importance for good refrigerated transport. It has to be assumed that the product is already at

the proper temperature at the time it is loaded in the transport vehicle, and that the vehicle is pre-cooled to the proper temperature before the product is loaded inside the vehicle. If the product does not generate any inside heat, temperature control is only a matter of absorbing any heat which can penetrate through the wall, ceiling, floor, or doors.

If the insulation of the transport vehicle is of good quality and adequate thickness, and if the vehicle is well constructed without heat transfer bridges or air leakage, then the amount of heat penetration inside the vehicle will be minimal, regardless of the outside temperature, and any kind of small refrigeration system will be able to handle the heat load.

Conversely, if the insulation of the transport vehicle is of mediocre quality or is not thick enough, and if the vehicle is poorly constructed or maintained with excessive air or heat leaks, then a tremendous amount of heat will penetrate inside the vehicle, and only a very powerful refrigeration system will be able to handle the heat load.

In both cases, the fact remains that the quality of the refrigeration system will depend on its ability to maintain the temperature of the product transported at the predetermined level originally established, without any human intervention, verification or adjustment. If this predetermined level is not maintained, there will be a progressive warming or cooling of the load that will eventually result in spoilage or poor quality of the product transported. Also, even if the predetermined level is respected overall, it might be accomplished in a haphazard way with a temperature spread around the set level that is much wider than appropriate.

It is currently accepted that a good refrigeration system will limit the spread to ± 1°C, and an excellent refrigeration system to a spread of ± 1°F or ± 0.5°C. This exacting requirement is relatively easy to achieve when the trailer is empty. It is much more difficult to guarantee when the trailer is fully loaded with boxes which have a tendency to obstruct a good dispersal of the cool air. This is why it is believed that a good air turbulence, to dislodge heat accumulation, will do a better job than high-velocity cool air, which will usually go around the load, not inside it.

### 3.5.2 Ability to pre-cool or to re-cool Cargo Space at a predetermined level

Most systems will require a fairly long time to bring the temperature of the cargo space to the set temperature before loading the product to be transported. This can take up to 3 or 4 hours of operation with the electric or diesel motor. This is much too long and, more often than not, this pre-cooling is not properly done. The product to be transported is, in fact, expected to do part of the cooling job. This is not a good practice, as the entire load will warm up by a few degrees before the temperature starts to drop. Similarly, re-cooling of the

cargo space has to accur whenever the doors are opened for delivery, and, if the capacity of the refrigeration system is not strong enough, there will be a progressive warming up of the cargo space.

With Cryogenic $CO_2$ Refrigeration, it is possible to obtain a very fast and very powerful pre-cooling or re-cooling of the cargo area by the use of a manual or automatic Coldspray.

3.5.3 Ability to decrease the temperature of the products to a predetermined level and maintain it

This feature is difficult to discuss because this is where the most abuse and false concepts circulate in the industry. Normally speaking, a transport vehicle is not supposed to do this work, and it is a questionable practice to pretend that the equipment can do it unless it has specifically been designed to do so.

It is true that most mechanical systems have so much more refrigeration capacity than needed for most of the year, that it is tempting to claim that it does not matter too much at what temperature the products are loaded, because the refrigeration can bring the temperature down relatively quickly. In reality, this is incorrect, because even if the system can do it, the type of cooling provided is not the type of cooling required to do the job properly. The high-velocity air does not adequately penetrate inside boxes of lettuce which have not been properly vacuum-cooled, and meat carcasses are not properly chilled by a high-velocity draft which tends to dessicate the surface of the meat instead of extracting the heat from inside the meat.

For a refrigeration system to be able to claim the added capability of cooling down some specific products, it has to be proven that the type of extra cooling available corresponds to the products' requirements, and does not in effect harm the perishables transported. If this is the case, it is better not to use the extra cooling capability, and only transport products which are already at the proper temperature when loaded.

3.5.4 Ability to cope with humidity

One of the problems faced by mechanical refrigeration is that excessive humidity will frost the system so quickly that the defrosting cycle will be too frequent or that the refrigeration system will lose most of its capacity. On most older machines, the defrosting cycle is operated by a timer and the defrosting takes place, needed or not, according to this fixed period. This might be too often, or not often enough. In either case, the average temperature of the load is affected and, in some extreme cases, it becomes impossible to maintain the set temperature, as when the humidity is very high outside, and the doors are opened too often.

It is our opinion that the Cryogenic $CO_2$ System can properly handle the defrosting aspect of the problem.

## 3.6 Sound transportation procedures

Regardless of the quality of the refrigeration system used, sound transportation procedures must be respected.

### 3.6.1 Loading and unloading

Loading and unloading of the product should be done speedily and, as much as possible, inside a dock which is protected against climatic extremes. It does not take long for a perishable product to be affected by a brutal change in environment.

### 3.6.2 Pre-cooling

The cargo space must be pre-cooled at the right temperature before the products are loaded, and the products should be loaded at the temperature at which they are to be transported. It is only in some specific circumstances that it is acceptable, or even desirable to load the product at a temperature higher or lower than optimum. In such cases, all parties concerned should be aware of the situation, so as to make sure that appropriate dispositions have been taken to execute the transport function in the best conditions.

### 3.6.3 Stacking Techniques

Products should not be loaded indiscriminately. There is a proper way to load boxes, bags or pieces, depending on their size and weight. The technique of transporting products loaded on pallets, slip, or "en Vrac" are not the same for every product, and great care should be taken to load the cargo space in such a way that the air circulation inside the transport vehicle is not affected. Sometimes it takes only a few parcels poorly placed inside the vehicle to affect the whole quality of the refrigerated load.

### 3.6.4 Packaging Technology

Over time, packaging manufacturers, working with food manufacturers, have developed packaging materials particularly adapted to a specific type of product. Usually, this selection will have been made taking into account the problems facing the transport industry. Unfortunately, every so often the packaging materials are not at all adapted to transportation requirements, and do not allow any system to successfully transport the product.

### 3.6.5 Door opening and closing

This is essentially a problem which affects local transportation, If the transport is properly done, it is possible to limit the disastrous effect of multiple door openings. Even so, the proper re-cooling of the load will always remain a major problem for the transport industry.

### 3.6.6 Preventive and regular maintenance

Obviously, no good refrigeration system can be operational without a regular preventive maintenance schedule; the complexity of the maintenance programme will depend on the complexity of the system. New equipment is so complex that it requires a tremendous amount of maintenance. Sometimes, to minimize the importance of the maintenance program, the preventive maintenance instructions are systematically limited to make them sound simple and inexpensive to follow. This might be true for the first two years, but the the situation alters after that.

Every user will agree that the cost of maintenance of a refrigeration unit will increase tremendously with the age of the unit and that it is very difficult to establish an average cost of maintenance which reflects actual conditions. This should not be the case with Cryogenic Refrigeration. The simplicity of the system should permit the evaluation of the preventive and regular maintenance cost so that it can easily be incorporated into the fair cost of operation, and remain essentially the same through the years.

## 4. CHARACTERISTICS AND IMPORTANCE OF REFRIGERATED TRANSPORT IN CANADA PLUS ADDITIONAL POTENTIAL IN NORTH AMERICA

### 4.1 What is meant by perishable food products ?

Most food products are perishable in the sense that they cannot be left unprotected indefinitely. But this perishability is only relative in the sense that unless the products are poorly handled or left in extremely adverse atmospheric conditions, they will maintain their quality for a fairly long time. Cereals, and most processed foods such as canned foods, pickled or dried products fall into this category, and are obviously not the subject of this study as they can be transported everywhere without difficulty or special care. Other products, on the contrary, must be kept at a specific temperature to preserve their quality for any length of time.

For some products, like fresh potatoes, this temperature does not have to be very precise, and fairly large variations are tolerable as long as the product is properly ventilated. Only freezing and very hot extremes will have to be avoided. For other fresh products, this temperature will be much more specific with little vartiation to avoid quick spoilage, especially if the product has been treated after harvesting or slaughtering, or been washed, or handled while being packed in its shipping carton, or - even worse - is in the middle of a transformation process. Most fresh fruits and vegetables, fresh meat, fish, poultry and dairy products fall into this category.

Finally, many products - after they have been completely processed - are in a particularly perishable state and require a very precise temperature to keep for any length of time. In most cases, this consists in maintaining the perishable product at a temperature close to the freezing point to slow down the growth of bacteria and the natural "breathing" of the product. In other cases, the temperature has to be maintained relatively high above 0°C (such as with tropical products or bakery products) to maintain the flavor and stability. Finally, in extreme cases, products have to be maintained frozen or even subfrozen, sometimes for long periods of time without excessive temperature fluctuations.

### 4.2 What is meant by "Refrigerated Transport" ?

From the time the handling of the perishable product begins until the time it is consumed, these products enter into a controlled atmosphere which is now called the "Cold Chain". This means that, to be preserved in top condition, the product has to be maintained at a pre-determined, specific temperature (which can vary at certain times during the marketing process),regardless of climatic conditions. During the time the product is transported from one point to another, it has to be maintained at the proper temperature. This "link" of the "Cold Chain" is known as

"Refrigerated Transport".

During the hot days of summer, the temperature of the transport vehicle will have to be lowered sufficiently to counteract any heat infiltration from the outside which could affect the specific temperature desired, which can vary from 15°C to 0°C, -20°C, or even -30°C. Similarly, during the cold months of winter, the temperature of the vehicle might have to be increased to avoid the exhaust of the internal heat of the product toward the outside, risking possible freezing or spoilage. But, most of the time, the refrigerated transport has only to maintain the temperature of the product at a set point with minimum temperature fluctuation and without affecting the intrinsic quality of the product transported, according to the factors described previously.

It should be emphasized again that this link of the Cold Chain, which is called "Refrigerated Transport", is not a processing link. This means that the refrigerated vehicle is expected to absorb any heat which could be generated by the perishable product during the transport, but should not be expected to remove heat from the product which should have been cooled before the transport began.

The perishable product has to be loaded at the proper specific temperature for transportation - not higher, not lower. If it is not, the vehicle has to correct this, by doing something that it is not built to do properly, and to pretend otherwise is false representation, unless it can be proven that the refrigeration unit has been specifically built to do such a specific job in addition to its basic refrigerated transport mandate. For example, cooling down semi-chilled carcasses of meat during the transport operation should not be done unless the vehicle and the refrigeration unit have been developed for this specific application.

## 4.3 Refrigerated transport in Canada

### 4.3.1 Importance

On land, transport is effected by either railroad, road or intermodal systems. All three modes of transport concern this study as containers and trailers can travel on the roads or on railroad platforms indifferently, and perishable products can be transported in either railcar, truck, trailer or container for the same destination. Currently, about 10,000 refrigerated trailers and 600 refrigerated railcars are registered in Canada. To these quantities must be added the American equipment which is used to bring perishable products into Canada from California, Arizona, Texas, Florida and many other States. In the United States, there are about 175,000 refrigerated trailers and 12,000 refrigerated railcars in operation. This is almost twenty time more equipment than in Canada.

To this amount must also be added part of the world inventory of 165,000 refrigerated containers and 70,000 insulated porthole

containers which are often used on North American roads. The North American refrigerated-land-transport fleet is consequently considerable, and is definitely an interesting market to investigate for potential penetration.

### 4.3.2 Local Transport

Local transport can be defined as a relatively short-haul round trip, less than 200-km or a 4-hour drive, carrying a variety of products of various characteristics, or making multiple stops. Most of the time, this traffic uses relatively small delivery vehicles, trucks or small vans to avoid traffic and parking problems.

### 4.3.3 Long-Haul Transport

The characteristics of this type of transport read as follow:
- The equipment used are heavy trucks, pop trailers 10 meters or less (35' or less), trailers or semi-trailers 12 meters and more (40' and up to 52' long).
- The trips last from 1/2 day to 6 days.
- The products are uniform and either fresh, chilled or frozen, and in full loads.
- Drop deliveries, if any, are limited to one or two stops at the end of the trip.

### 4.3.4 Transporters

Transporters are either public or private.
- Public transporters handle most of the real long-haul refrigerated transport because they are able to secure return freight for their equipment, thus eliminating back-haul losses; but they have to be equipped to transport various types of perishable food products: fresh, chilled, frozen or subcooled.
- Private transporters make limited real long-haul trips, but provide an extensive specialized transport from one specific point to another (where they can secure most of the time a return load). Since they transport their own merchandise, they can specialize their equipment to meet their specific requirements, and they can consequently optimize their use.

Public transporters operate at an average of 95% cost/profit ratio. Private transporters often operate at an even higher ratio, since they do not need to show a profit. Given this high ratio of costs to profit, any decrease of 1% in costs will result in a 20% increase in profits (all other factors being equal).

## 4.4 Characteristics of Current Long-Haul Refrigerated Transport

### 4.4.1 "Bigger and Bigger every day"

This is the expression which can best describe this industry for the last 6 to 8 years, and here are the characteristics:

- Hauls are longer because road transport increasingly replaces rail for perishable food products.

- Tractors are huge, designed to operate 24 hours a day, weeks at a time, with two drivers.

- Trailers are now up to 16 meters (52') long, 260cm (102") wide and 4 meters (13'6") high, to ensure maximun loading capacity.

- When ambient temperatures are 37.8°C (100°F), Mechanical Refrigeration units develop up to
  45,900 kJ/h (43,500 Btu/h) at 1.7°C (35°F)
  22,100 kJ/h (21,000 Btu/h) at -17.8°C (0°F)
  11,600 kJ/h (11,000 Btu/h) at -29°C (-20°F)

- They use huge 27 hp diesel motors and 500 $cm^3$ (30 cu.in.) compressors equipped with all types of controls and gadgets to operate in various conditions.

4.4.2 Drawbacks

All these innovations naturally have their draw-backs:

- Too often, to gain maximum loading capacity with minimum weight, the insulation of the trailer is sacrificed. The new "thin-wall" trailers (6cm or 3" overall side thickness), which had been developed to accommodate the 250 cm (96" trailers and permit the loading of 100 x 120cm (40" x 48") pallets, are still manufactured even though the width of the trailers has been extended to 260cm (102"), which would permit a return to adequate insulation.

- As the size and volume of the trailer increases, the refrigeration unit manufacturers have to increase the intensity of air circulation through the trailer to ensure proper refrigeration throughout the load (up to 4 air changes per minute). This air circulation is not good for most of the products transported, but is required to avoid hot spots through the load.

- The more sophisticated the refrigeration unit becomes, the more complicated, fragile and prone to mechanical problems it becomes.

- So many parts are involved, and adjustments are so precise, that the preventive maintenance of this equipment becomes a specialized, full-time job. However, if this preventive maintenance is not done, the equipment will age very quickly, and very high repair and maintenance costs will have to be incurred to maintain the unit operational.

- If, in spite of all this maintenance, the equipment fails, then it is a catastrophe. Because the equipment is so complex, the driver is unable to fix it and, because there is such a limited amount of insulation on the trailer, the heat gain cannot be stopped for long. As a result, the whole perishable load turns bad.

- Claims are not small any more. In the past, since only a few products had been affected by hot spots during the trip, and, since most of the load was still good, it was possible to settle for a reasonable price. Now, in the case of cold-chain failure, the resulting claim is usually much more than the cost of transport, often even more than the value of the load.

## 4.5 Importance of Long-Haul Refrigerated Transport of Perishable Food Products in Canada

Without going into detail, 3 groups of products consumed in Canada require refrigeration of one kind or another during transport. (See appendix B, page 25).

| | |
|---|---|
| Dairy products | 3,800,000 metric tons per year |
| Fruit & Vegetables | 3,500,000 metric tons per year |
| Red meat, Fish & Poultry | 3,200,000 metric tons per year |

Rail transportation represents less than 1,500,000 tons. The reason this traffic is relatively small is that the railroad lacks flexibility, the transport is too slow, and, in fact, the rail companies are not currently very interested in promoting this type of transport because they are losing money with the obsolete equipment that they operate.

Road transportation is very important in Canada for transport of fresh, chilled and frozen food products. However, statistics on the distances each load or commodity are transported are not easy to obtain, as a large part of the transport is done by small common carriers or by integrated industrial fleets which are reluctant to reveal information for competitive reasons. It is consequently difficult to establish with certainty the relative importance of long-haul refrigerated road transport as compared to what could be called local, or short-haul transport. It is a known fact, however, that dairy products are subjected to long-haul transport less often than fish or meat products, for example.

Based on the origins of the production or transformation, and the centers where the products are consumed, it can be safely said that more than half of the refrigerated volume consumed in Canada has to be carried by long-haul, and that, consequently, the long-haul road volume transported is close to 5,000,000 tons.

Short distance transport is, unfortunately, too often subjected to mishandling (such as lack of refrigeration), but the damage is not usually too great or too obvious. However, as stated before, long-haul transport cannot afford any kind of breakdown in the "Cold Chain".

Products which will benefit most from $CO_2$ Refrigeration are those which cannot be left for any length of time without proper refrigeration because of their great perishability, such as small fruit and leafy vegetables, or susceptibility to an extensive growth of bacteria when maintained above 0°C - such as fresh meat,

fish and poultry. There are also the products which have a high unit value, either because of their intrinsic scarcity, of because of the value added through processing or conditioning (including freezing). In all cases, the cost of replacement - if spoiled - is excessive and unwarranted.

The following list will give an idea of these products:

- Red meat: fresh, chilled and frozen, and meat products.
- Fish: fresh, chilled, frozen and crustacéans (shell - fish).
- Poultry: fresh, chilled, frozen, and eggs.
- Seasonal fresh fruit and vegetables.
- All frozen products
  - Dairy, ice cream and sherbet;
  - fruit, including citrus juices;
  - vegetables, including potatoes;
  - prepared dishes (TV Dinners).

## PART II - TECHNICAL STUDY AND TESTING

The objective of the technical study was to determine, among the various cryogenic techniques available, which alternative would be most appropriate to apply to the various factors that constitute good refrigerated transport; and then, just as importantly, to determine how the selected techniques should be implemented to get maximum efficiency and dependability.

To obtain this objective, a concept was developed based on what was believed, at the time, to be the proper answer to the problem at hand. Then, as the expected results did not materialize, following extensive testing, new concepts were developed which took into consideration the new information acquired during previous testings. This type of approach is often referred to as the "trial and error approach" and is frowned upon by some purists. However, it is well-known that the results obtained by this method are much less theoretical and much more practical. When you work with liquid and gas dynamics applied to heat transfer, it becomes very tricky and misleading to make endless theoretical calculations and extrapolations on a table-size model. Using a full-size model, on the contrary, permits the development of real usable data. In particular, this approach permitted us to progressively harness the cryogenic process in a way not previously attained to the best of our knowledge of existing cryogenic systems.

### 5. PRELIMINARY CONCEPTUALIZATION (MARCH 14, 1986)

On March 14, 1986, at the end of Phase I of the project, a preliminary conceptualization was tabled which was based on what was believed, at that time, to be the solution to good cryogenic transport refrigeration.

#### 5.1 Techniques used

This preliminary conceptualization made use of three basic techniques used by Concool Refrigeration Ltd. when they developed the Cryogenic AFFCAR Railcar 2001, (tested extensively in the United States in 1983 and 1984). Some of these techniques were patented, and Fridev made an agreement with Concool in 1985 for the use of these patents .
The three basic techniques are :

### 5.1.1 The Coldspray

This procedure will cool the interior of the cargo space and offer a high degree of temperature control. As temperature probes indicate a requirement for cooling, the demand injector will inject $CO_2$ snow for a short preset time, then wait an additional predetermined time to allow the probes to react and establish if the required temperature is reached. If additional cooling is required, the procedure is repeated. This method gives a controlled degree of cooling and limits consumption of $CO_2$.

The Coldspray can operate inside the cargo area or inside a vapor-proof bunker in the roof when it is not advisable to have the $CO_2$ in direct contact with the transported merchandise. The injections can be timed to match the natural losses of the box which result from air leakage, so that no cooling capacity at all is lost. Coldspray is a unique way of pre-cooling a trailer quickly and efficiently before loading it with perishable food products or re-cooling it after it is loaded. This procedure will eliminate damaging fluctuations in temperature during the first hours of transport.

### 5.1.2 The Coldsink

This method will cool the interior of the cargo space, and offers the ultimate in temperature control. The patented Coldsink system uses a completely different refrigeration concept, based on the direct relationship between the pressure of liquid $CO_2$ and its temperature. It consists of a network of interconnected pipes and/or pressure vessels filled with liquid $CO_2$ held at a specific temperature, equal to the temperature desired for the load, which completely surrounds the cargo box and merchandise and acts as a barrier to heat penetration. A dial is set to the required temperature, and this information is directly converted to pressure requirements. As $CO_2$ and the entire enclosed Coldsink network is always at exactly the same pressure, the temperature throughout the system will always be exactly the same. Since temperature fluctuations do not occur, this system will achieve the ultimate degree of cooling, and therefore result in high product quality, and the most efficient use of $CO_2$.

As the $CO_2$ utilized in the Coldsink system is contained within an enclosed circuit, this system has the additional advantage of preserving an oxygen atmosphere, if so desired.

Essentially, the Coldsink system is similar to a miniature jacketed storage technique, which is widely accepted in the storage of highly perishable products. The great advantage of jacketed storage is that it surrounds the stored products with air at exactly the proper temperature, but which is not in direct contact with the product. Consequently, the proper environment is created without using high velocity air which has a tendency to dessicate the product. Every area of the cargo is at the same temperature, as the Coldsink acts as a barrier to heat infiltration and absorbs the internal respiration heat of the

products. Also, because there is no evaporator, there is no defrosting cycle, as with a mechanical unit, and the humidity in the cargo box can remain very high, if desired.

The Coldsink system can vent its excess pressure inside or outside of the cargo area depending on the option adopted and whether or not a $CO_2$ atmosphere is desired.

5.1.3 The liquid $CO_2$ Reserve

The $CO_2$ Reserve can be located inside or outside the cargo box. It can be exposed to the cargo as a giant Coldsink or it can be heavily insulated to eliminate evaporation when not in use. The size of the Reserve has to be determined to guarantee enough liquid supply until the next fill up, without over-burdening the transport vehicle. The Reserve tank has to be a pressure vessel wich meets very stringent safety requirements. It is foreseen that for the road transport system to be developed, the $CO_2$ Reserve and the Coldsink will operate at two different pressures so as to accommodate chilled products (up to 30 bars or 450 psi) and keep the reserve refrigerant at the most efficient pressure (13 to 20 bars or 200 to 300 psi).

## 5.2 The wrap-around Coldsink concept

The schematic design of the preliminary conceptualization tabled on March 14, 1986 (see figure 1), clearly indicates that the use of these three elements described above is planned, including a new element "the Heatsink" which had to be developed. The preliminary conceptualization contained the following elements:

a) Coldsink
The Coldsink will surround the cargo box on every side except the back door. The Coldsink elements are made of piping properly spaced and lodged between two heat-sensitive liners. The cargo-side liner is made of resistant material to protect the piping from forklift abuse and permit easy clean-ups. The insulation-side liner is light and directly in contact with the insulation. The Coldsink on the floor is made up of larger piping than the balance of the system, in order to face additional heat gain. An air space is provided above the Coldsink in the roof and forms a false ceiling, which must be airtight.

b) Coldspray
Coldsprays will inject snow and vapor either inside the cargo box or inside the air space provided above the interior Coldspray nozzle, depending on the type of product transported. They can be used for quick pre-cooling of the cargo box before loading starts, if positioned inside the cargo box. If used inside the false ceiling, the cold vapors coming from the Coldsink will be recuperated and used with the dry snow to help maintain the Coldsink at the correct temperature. The cold mix (vapor and snow) will filter down along the sides of the Coldsink and will be pushed toward the end of the trailer. At the end of the trailer, a curtain will direct the pressurized air, saturated

with $CO_2$, towards a vent at the base of the back door so that $CO_2$ is not introduced into the loading area itself.

c) Reserve Tank
The Reserve tank will either be in the nose or under the trailer (depending on the importance of the reserve selected) and will be properly insulated. Filling of the Coldsink will start from the center piping in the floor to the edges of the floor, then up the risers (front and sides), and finally into the piping in the ceiling, starting from the edges toward the center piping, where an exhaust valve will be located. The Coldspray nozzle and pressure release valve of the Coldsink signal the Reserve tank when liquid $CO_2$ is required in the system. The temperatures and pressures in the Reserve tank and in the Coldsink might be different, depending on the type of transport done and the supply of liquid $CO_2$ available.

d) Heatsink
At this point, a Heatsink was visualized which would heat part of the Coldsink, to maintain appropriate pressures in the Coldsink and, consequently, appropriate temperatures.
- When the Heatsink is in operation there should be no consumption of liquid $CO_2$.
- When the Coldsink is in operation there should be no consumption of Heatsink fuel.

Essentially, further development was a matter of properly balancing the interaction of these two systems.

e) Controls
Existing controls, which have been developed for separate functions, had to be re-designed to obtain a combination of functions. Some of the existing controls were eliminated to simplify the operation of the system, as long as accurate temperature readings were maintained. Pressure readings were converted to temperature readings to simplify the action of the operators.

## 5.3 Theoretical study by Dr.Charles Murphy and Brian Mori of McGill University

The approach used for this preliminary conceptualization was in line with the latest patents registered by CONCOOL REFRIGERATION LTD and proposed to use the Coldspray and Coldsink techniques inside a jacketed envelope rather than in direct contact with the cargo as previously done by CONCOOL and other developers.
The reasoning behind this approach was threefold:

1) The trailer had to be capable of carrying any type of perishable product, at various temperatures, whether or not it was susceptible to the presence of $CO_2$ in the atmosphere.

2) The extra cold temperatures resulting from the conversion of liquid $CO_2$ into dry ice and vapors when released at atmospheric pressures, are much easier to control inside a small enclosed

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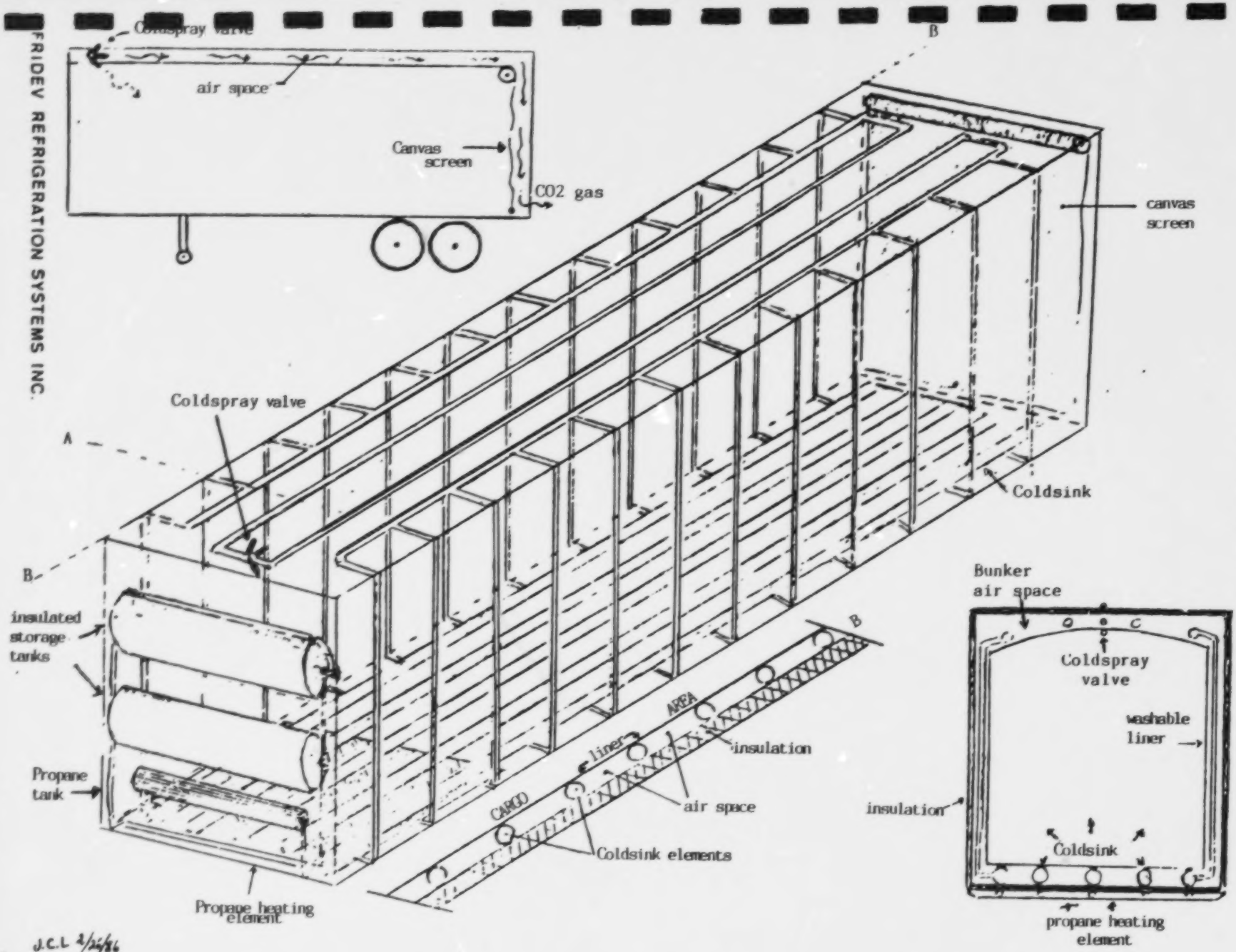


SCHEMATIC DESIGN (3/14/86)

FIG. 1

J.C.L 3/24/86

area than inside a 48' trailer loaded to the ceiling with products sensitive to temperature fluctuations.

3) Poorly controlled consumption of liquid $CO_2$ or production of dry ice affects economical competitivity of a Cryogenic Refrigeration system, and would make it very difficult to market in the long run. Even if the preliminary conceptualization was attractive and made sense in theory, it remains that its development, as a practical piece of equipment at a reasonable price, was not straightforward. So, before proceeding further with the development of a prototype, it was agreed to subcontract with Dr. Charles Murphy, expert in heat transfer at McGill University, to produce a study on the basic value of the Coldsink technology to refrigeration.

   Essentially, the study had to determine what should be the optimum spacing between the Coldsink pipes, so that the Coldsink plates could absorb whatever heat penetrated through the insulation of the trailer. This study had to be done for different ambient temperatures, different plate thicknesses, and liquid $CO_2$ under different pressures.

## 6. NEW CONCEPT (JUNE 27, 1986) AND LABORATORY PROTOTYPE TESTING

### 6.1 The straight-forward jacketed concept

The result of this basic study, conducted by Dr. Murphy and his assistant Brian Mori, suggested a rethinking of the concept and a commitment to giving more importance to the basic principle of physics "Heat rises and cold descends by simple convection". As a consequence, it was decided to use the Coldsink technology only as part of the void in the roof of the trailer, and to generate the additional cold eventually required in the sides, the door and the floor of the trailer solely by injection of $CO_2$ in the voids enveloping the cargo space, using the cold spray technology. (See Figure 2)

Similarly, it was agreed that the heating system to be developed should circulate heat in the void of the floor first, then through the voids of the sides and the roof and not inside the cargo area, the way most heating systems currently operate.

As the entire concept now depended on establishing a good circulation of cold or hot air inside the jacket, and as calculation of heat transfer by convection and conduction inside and outside the void was becoming extremely complex, it became obvious that only actual physical experimentation could confirm if the new concept had any chance of practical success. It was agreed that for the experiment to be significant, it should be carried out on a full size trailer or a piece of equipment as close as possible or practical to a full size trailer.

### 6.2 Laboratory test trailer selection

The laboratory test trailer was in fact a modified 40' steel container. For the purpose of "laboratory testing", a used container was chosen rather than a used trailer because :

1) It is relatively inexpensive to rent and is readily available.

2) The dimensions of a 40' container are close enough to a standard trailer to obtain valuable data during testing.

3) It is relatively easy to make modifications during testing because the container has its own independent structure.

4) The rental of a container chassis, whenever required to move the container around, is much less expensive than to rent a trailer train during the modification of the box and the stationary testing.

5) The container does not require registration as it is carried by a container chassis which is already registered.

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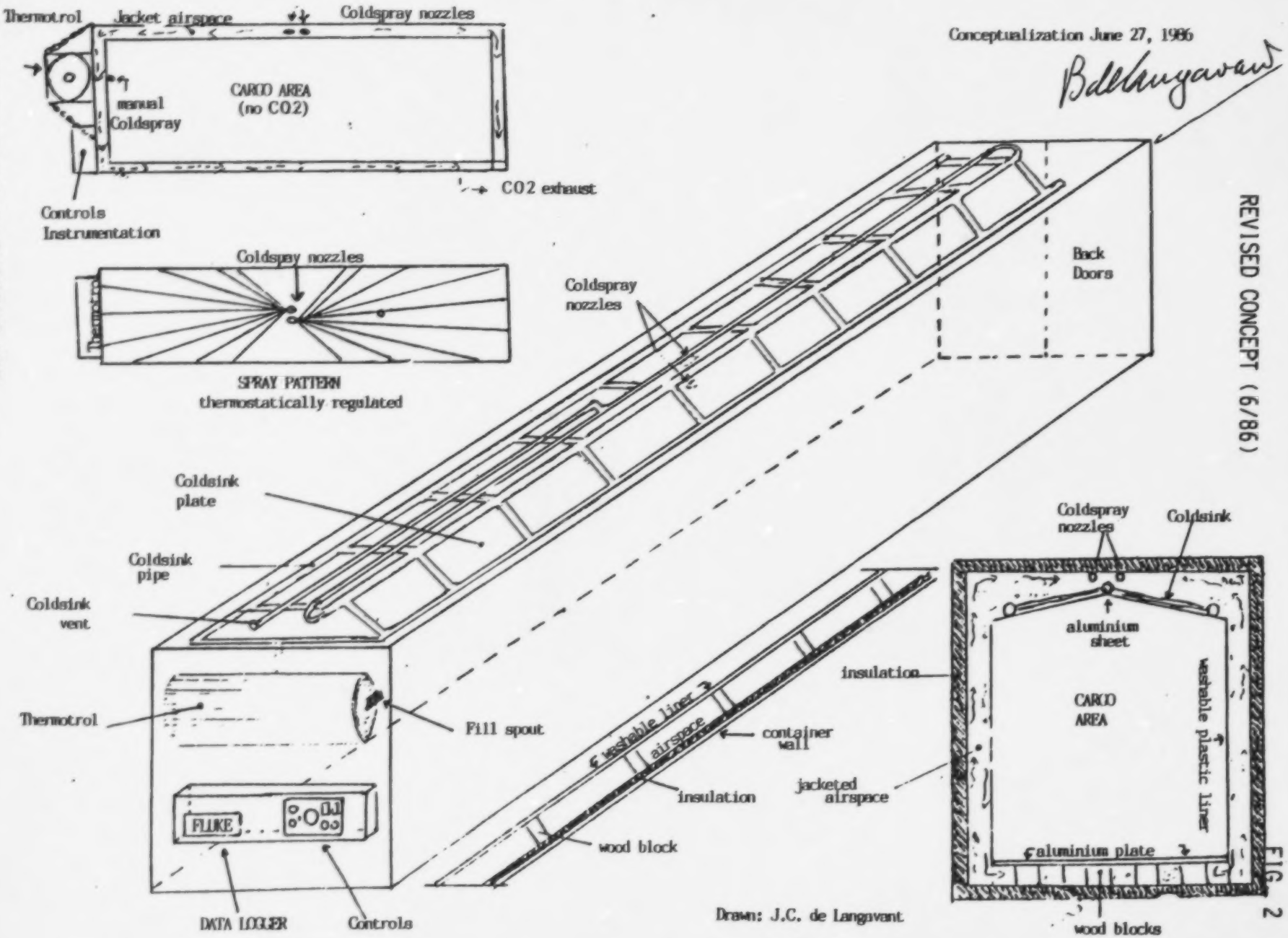


Conceptualization June 27, 1986

B de Langavant

REVISED CONCEPT (6/86)

Drawn: J.C. de Langavant

FIG. 2

6) Transporters (public or private) can use their own tractors without having to be concerned about the cargo (the refrigerated container) which has already received approval as being safe for transportation.

A 40' standard steel container rather than a reefer container was selected because :

1) Good used reefer containers are not readily available and they are relatively expensive to rent.

2) It is very difficult to evaluate and control the U factor of a used reefer container, as insulation wears out unevenly.

3) Most reefer containers have a compartment in the nose for the mechanical unit, which would reduce the cargo space even more.

4) The structure of a reefer container makes modifications more complicated and expensive to realize than with a standard steel container.

The used 40' standard steel container selected was in good condition and the back door fit tightly. It was constructed with 6" ribs, wooden floor, chassis neck and flat ceiling. It was customs-cleared and good for transport in Canada.

## 6.3 Container Conversion

The conversion of the 40' standard steel container to a 40' insulated jacketed trailer box was subcontracted to PORTE SEPT INC, and realized during the months of July and August of 1986. (PORTE SEPT INC is a repair shop, specialized in the rehabilitation or conversion of transport equipment, which works mostly with companies such as CN or Via Rail. The shop is well equipped to do this type of work, and the labor force is flexible and open minded.)

FRIDEV developed the specifications for the conversion, and PORTE SEPT applied its expertise. Wood blocks were attached to the floor, roof, door and inside walls of the container to ensure appropriate spacing for insulation spraying and satisfactory supports for the void spacers of the jacket. Insulation was 10cm (4") on the roof and front, 6cm(2 1/2") on one side, 9cm (31/2") on the other, 7.5cm (3") on back door and 5cm (2") on floor. The floor was also insulated 5m (2") under the carrying frame. Insulation was polyurethane sprayed in successive layers by a specialized contractor and covered by a plastic vapor barrier liner. It was estimated that the overall U Factor would be around 190 kJ/h/°C (100 Btu/h/°F). This was confirmed when the container was tested at the Blainville Test Center of Transport Canada on August 8 1986, and was rated for a U Factor of 193 kJ/h/°C (102 Btu/h/°F). Additional work on the door brought the U Factor below 190 kJ/h/°C (100 Btu/h/°F).

Above the wood blocks used for structure and insulation spacing, wooden blocks of the appropriate thickness were placed to create the desired voids as follows:

5cm (2") on the floor,
3.8cm (1 1/2") on the side insulated with 9cm (3 1/2") of polyurethane,
6.3cm (2 1/2") on the side insulated with 6.3cm (2 1/2") of polyurethane,
5cm (2") on the front and the back door.

The floor was then covered with a .6cm (1/4") aluminium grooved plate. The sides, including the door, were covered with a .9cm (3/8") finishing plywood covered with a plastic liner. The ceiling was closed by a 1.5mm (.063) gauge aluminium plate which was a component of the coldsink and which hung from the roof of the container. This aluminium plate was shaped as a long roof with a small slope 10 cm for 1.2 meter (4" for 4') with the highest point all along the center of the roof at 5 cm (2") from the top. The thickness of the aluminium plate was determined using Brian Mori's study.

## 6.4 The Cryogenic Refrigeration

The Coldsink which lined the void in the roof was made of 22 mm (7/8") copper piping with transversal 16 mm (5/8") copper piping placed at square angles and forming a series of rectangles, 80 cm x 120 cm (32" x 48"). The pipes were then solidly riveted to a 1.5 mm (.063) gauge aluminium plate and assembled to form the shape of a long roof inside the container with a 1-12 slope.

Temperatures of points on the plate furthest from the pipes might be 11°C (20°F) higher that the temperatures of the pipes but the average temperature spread of the Coldplate was never more than 4.5°C (8°F) above the temperature of the pipes. The temperature dispersion disappears a few centimeters from the Coldsink inside of the cargo space.

The pressure of the liquid $CO_2$ inside the Coldsink was set according to the temperature of the cargo to be transported. The Coldsink was suspended from the roof of the container and attached by wooden blocks; the void so obtained was 15 cm.(6") on the sides and 5 cm (2") in the center at the top of the Coldsink.

The exhaust vent of the Coldsink was at the highest point of the piping where vapors accumulated before being ejected from the Coldsink, to bring the pressure back to the required setting, and maintain the desired temperature in the Coldsink piping. These vapors were then transferred by a pipe to the void under the floor of the trailer, as this area was the most difficult to keep cold.

Two opposite Coldspray nozzles were installed in the center of the jacketed space in the roof and were pulse activated by two independant thermostats placed in the wall voids. Whenever the

temperatures in the wall exceeded the predetermined settings, the Coldsprays would send a jet of $CO_2$ dry ice into the jacketed air space for a very short time. Then it would wait a predetermined amount of time before activating again.

The Coldsprays remained active as long as the proper temperature was not reached in the wall voids. In addition, a manual Coldspray nozzle was mounted inside the cargo area to permit fast precooling of the cargo space before loading, or to quickly expel any heat out of the cargo space after a door opening.

To ensure liquid $CO_2$ supply to the laboratory test container, a recuperated THERMOTROL portable cryogenic vessel was used. This equipment was already approved for road transport and had a capacity sufficient for adequate supply of $CO_2$ during laboratory testing. The mounting of the Thermotrol on the container was very simple, as it had been developed originally as a clip-on unit for sea containers.

The controls for the cryogenic refrigeration equipment were all pneumatic and were regulated by the pressure of the liquid $CO_2$ only. No other source of energy was required to activate the system and accurately control it. The control settings were extremely simple and were located in very accessible points.

## 6.5 The heating system

Several alternative heating sources were considered. It was felt that the simplest way to resolve the heating problem was to use Glycol circulated inside a piping loop in the floor and warmed up by a propane heather. This system has been developed by VAPOR CANADA and is used to heat rail cars.

Consequently, copper pipes to be used as radiators were placed in the void under the floor to insure the heating of the trailer when outside temperature would be lower than the temperature of the cargo transported. The basic idea consisted in using the void network created inside the container to also ensure the heating of the cargo.

## 6.6 Testing equipment and programs

Temperatures were constantly monitored with 80 thermocouples placed inside the jacketed envelopes (Door, Floor, Walls, Roof), inside the cargo area (Ceiling, Product, Air Space), directly in contact with the Coldsink or outside the container to monitor ambient temperatures. Even if rudimentary, these thermocouples were quite accurate and responded quickly to temperature fluctuations and have been calibrated to ± 1°C. These thermocouples were permanently connected to a Fluke Data Logger 2280B which had been rented for the testing period. The Fluke Data Logger is equipped with a printer and a magnetic tape, on which data can be recorded for hours without being attended. Also specific channel readings can be obtained at any time on demand,

and permit very precise adjustment of the controls. Pressures in the Reserve $CO_2$ tank and in the Coldsink were constantly monitored on the Fluke with pressure transducers situated at several points of the system, thus permitting the required adjustment of the various controls.

These pressure transducers were activated by a 12 V battery with the voltage precisely regulated at 10 volts. Consequently, the readings obtained were very accurate.

Several programs were developed to acquire and then analyse the desired information on the Fluke.

The most frequently used was a complete scanning of all thermocouples and pressure transducers at a predetermined interval, for example, every 15 minutes.(See figure 3). Another feature which was very helpful consisted in the regrouping and averaging of thermocouples located in a specific place such as floor, wall, ceiling or cargo, as this gave average temperatures and eliminated insignificant fluctuations. These groups or pseudo channels were then plotted at regular intervals (e.g, 10 seconds) on the printer, and permitted an immediate analysis of the overall operation of the system. (See figure 4).

Recorded data on the Data logger tape were down-loaded, with a Prologger program developed by Fluke, on to a portable Toshiba 3000 Plus, where they were translated and compiled with a Lotus 1,2,3 program, which permitted any analysis required to probe and perfect the system.

By this time it was autumn and it was not conceivable to test the container outside during the winter months and obtain meaningful results. If was consequently decided to place the container inside ashed heated at 21°C (70°F) and to load it with 16 tons of wheat at 14% humidity in bags of 40 kg to act as perishable cargo which could be tested at various temperatures without hurting the product too much and while still obtaining a certain reaction to temperature changes.

Everything was then ready to start the testing of the laboratory prototype and to evaluate if the various components where reacting properly in order to maintain the cargo at a preset low temperature while the enviroment was maintained at a steady 20°C (70°F) temperature.

## 6.7 Testing of the system

Actual testing started in November, 1986 and continued into January, 1987. Most of the tests conducted in November and early December consisted in scanning, at regular intervals the various thermocouples placed in the prototype, and then averaging the readings by groups to develop trends in the operation of the $CO_2$ refrigeration system. This approach made it possible to confirm by mid-December that the system was operational and that adequate refrigeration could be obtained by combining the action of the

FIG. 3

SCANNING

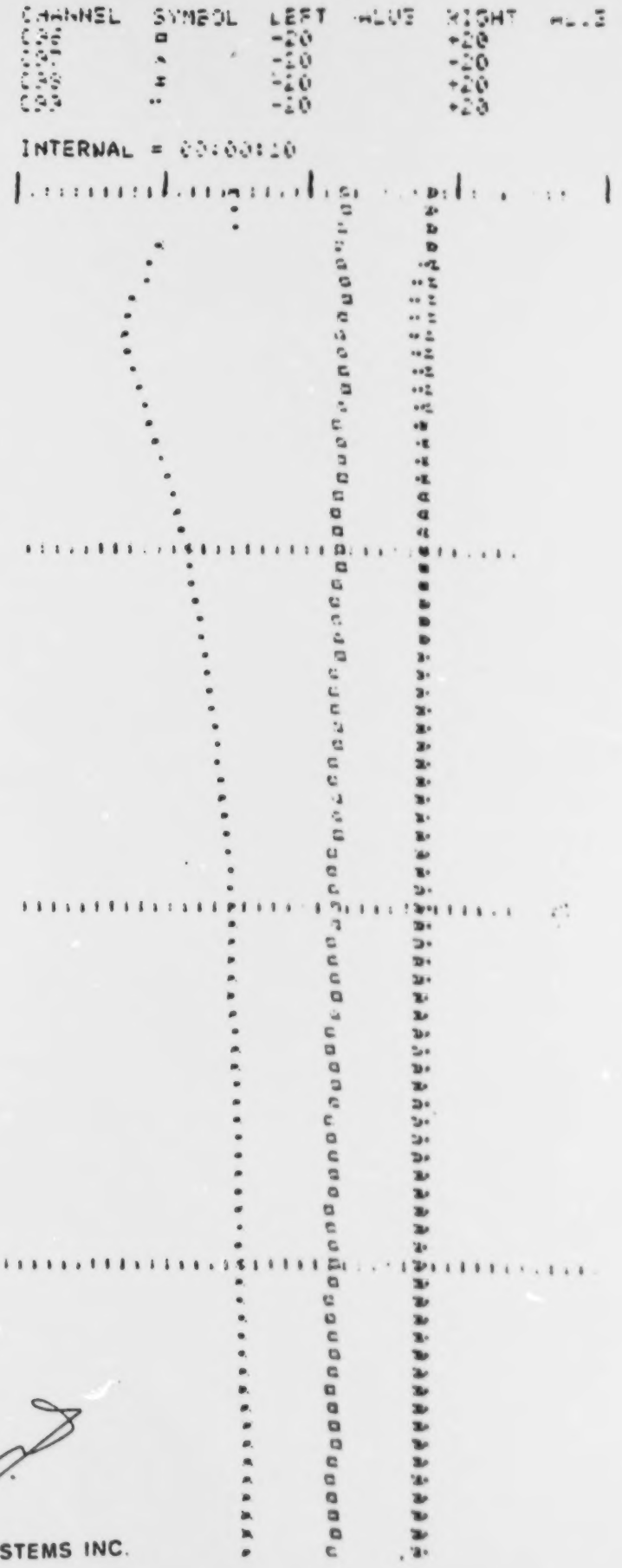


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FIG. 4

## LOTUS PRINT FILE (FROM PROLOGGER)

```
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"13:03:22"
1
"  1"    3.7 "  2" -  2.5 "  3" -  0.4 "  4"    7.0 "  5" -  0.8 "  6"    3.2 "  7" -  0.2 "  8"    4.4 "  9"    0.0
" 10" -  0.3 " 19"    4.0 " 20" -  2.2 " 21"    0.5 " 22" -  0.5 " 23" -  4.1 " 24" -  0.3 " 25" -  4.1 " 26" -  5.1
" 35" -  2.9 " 36" -  5.9 " 37" -  6.4 " 38" -  5.2 " 39" -  7.3 " 40" - 11.2 " 41" - 11.4 " 42" -  8.2 " 43" -  5.5
" 52" -  6.1 " 53" -  2.5 " 54" -  7.6 " 55" -  7.5 " 56" - 11.6
"23 NOV 86"
"13:03:33"
2
" 63" -  6.1 " 64" - 13.4 " 65" -  4.1 " 66" -  3.7 " 67" -  2.0 " 68" -  7.5 " 69"    7.3 " 70" -  1.3 " 71" -  5.4
"23 NOV 86"
"13:03:35"
3
" 57"   63.2 " 58"   61.3 " 59"   63.2 " 60"   55.8 " 61"   50.5 " 62"   55.2
"23 NOV 86"
"13:03:42"
4
" 93"  255.30 " 94"  271.53 " 95"  268.87
"23 NOV 86"
"13:18:19"
1
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" 10" -  0.6 " 19"    3.8 " 20" -  2.1 " 21" -  0.1 " 22" -  2.1 " 23" -  4.4 " 24" -  0.4 " 25" -  4.0 " 26" -  4.4
" 35" -  1.7 " 36" -  5.6 " 37" -  5.6 " 38" -  5.6 " 39" -  6.5 " 40" - 10.6 " 41" - 10.6 " 42" -  8.1 " 43" -  5.7
" 52" -  6.3 " 53" -  2.9 " 54" -  8.2 " 55" -  7.4 " 56" - 10.7
"23 NOV 86"
"13:18:29"
2
" 63" -  4.9 " 64" - 11.4 " 65" -  2.9 " 66" -  3.0 " 67" -  1.8 " 68" -  6.1 " 69"    7.3 " 70" -  1.4 " 71" -  4.1
"23 NOV 86"
"13:18:34"
3
" 57"   64.9 " 58"   63.7 " 59"   64.3 " 60"   59.8 " 61"   52.2 " 62"   59.4
"23 NOV 86"
"13:18:38"
4
" 93"  252.53 " 94"  289.48 " 95"  286.68 "  1"    4.5 "  2" -  2.4 "  3" -  0.3 "  4"    7.1 "  5" -  0.8 "  6"    4.3
" 15"    3.1 " 16"    2.3 " 17"    3.8 " 18" -  0.6 " 19"    4.2 " 20" -  1.3 " 21"    0.1 " 22" -  3.8 " 23" -  4.8
" 32" -  6.4 " 33" -  2.7 " 34" -  4.2 " 35" -  0.4 " 36" -  5.2 " 37" -  4.7 " 38" -  5.5 " 39" -  5.6 " 40" - 10.0
" 49" -  2.0 " 50" -  2.7 " 51" -  5.8 " 52" -  6.3 " 53" -  2.9 " 54" -  7.7 " 55" -  8.0 " 56" -  9.8
"23 NOV 86"
"13:33:29"
2
" 63" -  3.8 " 64" -  8.9 " 65" -  1.3 " 66" -  2.2 " 67" -  1.8 " 68" -  4.8 " 69"    7.5 " 70" -  1.2 " 71" -  2.5
"23 NOV 86"
"13:33:33"
3
" 57"   66.7 " 58"   64.7 " 59"   65.8 " 60"   61.0 " 61"   51.5 " 62"   60.1
"23 NOV 86"
"13:33:37"
4
" 93"  251.92 " 94"  259.88 " 95"  256.58
"23 NOV 86"
"13:48:19"
1
"  1"    5.4 "  2" -  1.8 "  3" -  0.2 "  4"    7.6 "  5" -  0.1 "  6"    5.0 "  7" -  0.8 "  8"    6.0 "  9"    0.3
" 10" -  0.3 " 19"    4.2 " 20" -  0.9 " 21"    0.4 " 22" -  3.5 " 23" -  5.2 " 24"    1.5 " 25" -  1.9 " 26" -  2.5
" 35"    0.5 " 36" -  4.6 " 37" -  3.6 " 38" -  5.1 " 39" -  4.6 " 40" -  9.5 " 41" -  8.9 " 42" -  7.6 " 43" -  5.4
" 54" -  6.6 " 55" -  8.8 " 56" -  9.0
```

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Coldsink and Coldsprays operating inside a jacketed air space. But problems could already be identified, and the purpose of the tests in the second part of December and in January were to determine if these problems could be progressively eliminated or if drastic action should be taken to overcome them.

Extensive tests were consequently conducted to determine the effects of the Coldsink and Coldsprays, working separately and together, on the pressure inside the system and on the fluctuation of temperatures inside the voids and the cargo space. For the pressure readings, measurements were taken at the rate of 3 1/2 per second, at various points of the system, for various pressure settings of the Coldsink, or timings of the Coldsprays.

For temperature fluctuation, readings were taken for each individual thermocouple every 15 seconds, showing the relation of the Coldsink or Coldspray operations and the progressive drops in temperatures everywhere inside the container and the void.

6.7.1 Results on Pressure Drop and Pressure Recovery

Each time the Coldsink vent opened, or the Coldspray operated, there was a very marked pressure drop in the system. The control of this pressure drop was really what would make the system operational, and was the key to efficient cryogenic refrigeration. An adequate pressure drop would permit the transfer of a certain amount of liquid $CO_2$ from the Reserve tank to the Coldsink and to the Coldsprays. If this pressure drop is too small, there will be no liquid flow into the Coldsink, or it will be insufficient. If it is too high, there will be overfilling and consequently overcooling.

For the purpose of testing, it was decided to install three pressure transducers on the system

Channel No 93 indicated the pressure in the Reserve tank.
Channel No 94 indicated the pressure at the level of the Coldsink vent.
Channel No 95 indicated the pressure at the beginning of the Coldsink - Coldspray system.

The pressure at these three points was indicated on visual pressure gauges which were not very accurate (about ± 5% apart), but the readings obtained with the transducers and the Fluke data logger were very accurate. For the same pressures, readings were less than one and a half pounds apart for 20 bars (300 lbs.), or consequently less than .5 of 1% of difference between the three transducers, which was more accurate than required.

Coldsink testing

For any set pressure in the system from 17 bars (250lbs.) to 23 bars (330lbs.), pressure drops in the Coldsink were monitored depending on the sensitivity adjustment of the Coldsink controller. (See figure 5). Actual drops occasioned by vent

openings, varying from 1 second up to 10 seconds and more, were analyzed (See figure 6). The time for pressure recovery required between two ventings, depending on the delta t or heat accumulation in the ceiling, was also monitored. This time could vary from 30 seconds to 3 minutes or more depending on the heat transfer rate.

The effect of the Coldsink on the overall pressure of the system was analyzed in depth, as well as the refilling process and how it was affected by the pressure drop.

These various tests supplied invaluable experience and understanding of what was taking place inside the piping system, and gave extremely valid knowledge on how to design the future system.

Coldspray testing

Similarly, the effect of the two Coldsprays on the pressurization of the system was extensively monitored. Coldsprays were tested with injections of 1 second up to 10 seconds and with intervals of 20 seconds up to 250 seconds. The various pressure drops and recovery times were monitored and analyzed in depth. (See figure 7).

The action of the two Coldsprays was monitored separately and concurrently by setting the controls accordingly. (See figure 8).

Coldsink and Coldspray testing

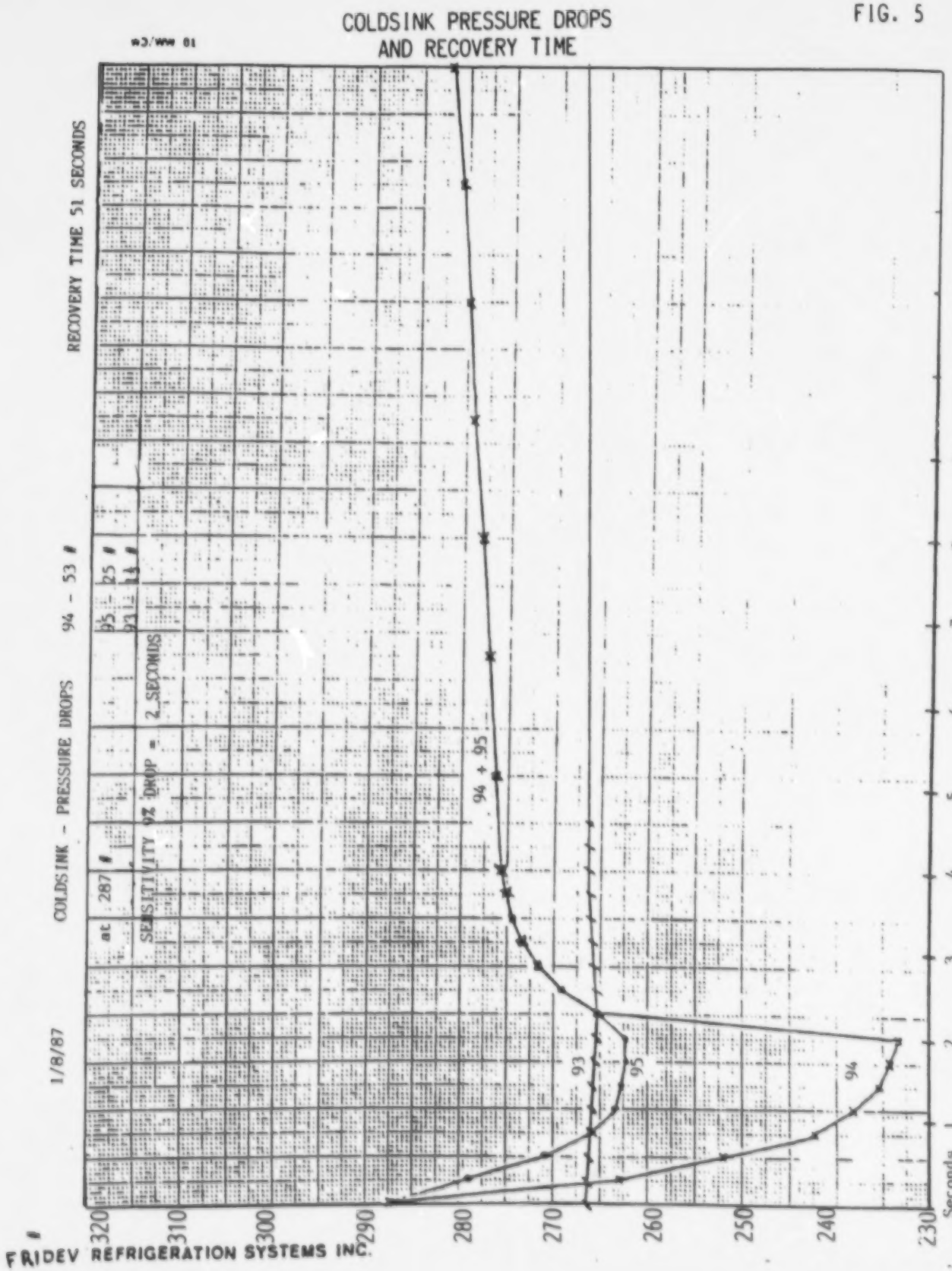
Subsequently, the various elements were made to operate together and the drops in pressure were carefully recorded and analyzed at the same time as the recovery time between operations. This is where the adequate combination and synchronization of the actions and reactions of the various equipment and controls come into play, and make the system work or fail. This experimentation was invaluable in designing the road prototype to guarantee permanent operation without close supervision.

6.7.2 Results on Cold Transfer Sensitivity

This aspect of the testing program confirmed what was already suspected in mid-December. Many scanning tests were conducted to analyze the reaction of the 80 thermocouples to the various elements of the refrigeration system. In these tests, each individual thermocouple was analyzed separately in the hope of identifying which ones could be selected for valid further testing.

Very good results were obtained in the roof and under the ceiling of the cargo space, as the circulation of air and the heat transfer were unobstructed.

FIG. 5

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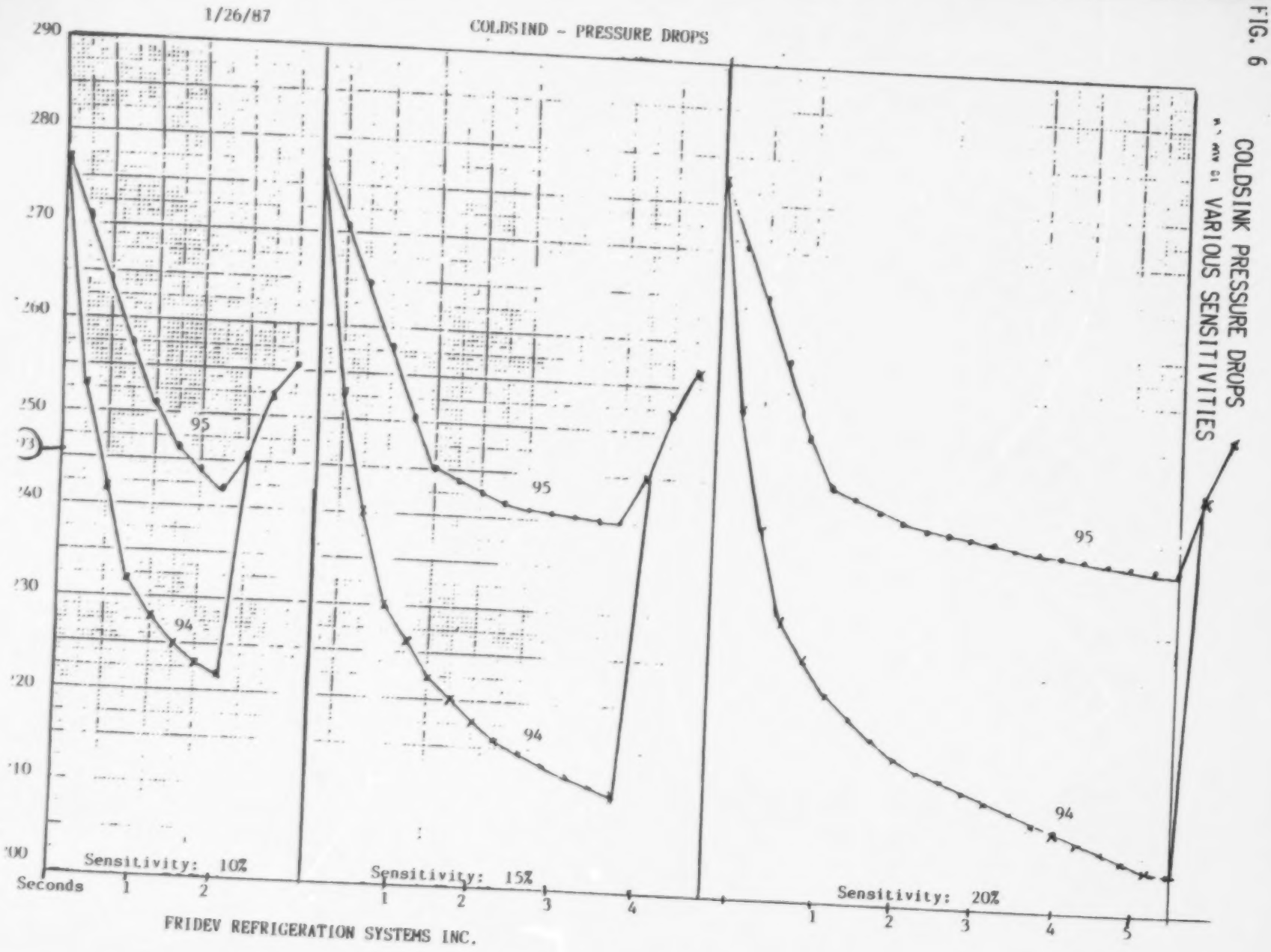



FIG. 6

COLDSINK PRESSURE DROPS
AT VARIOUS SENSITIVITIES

1/12/81

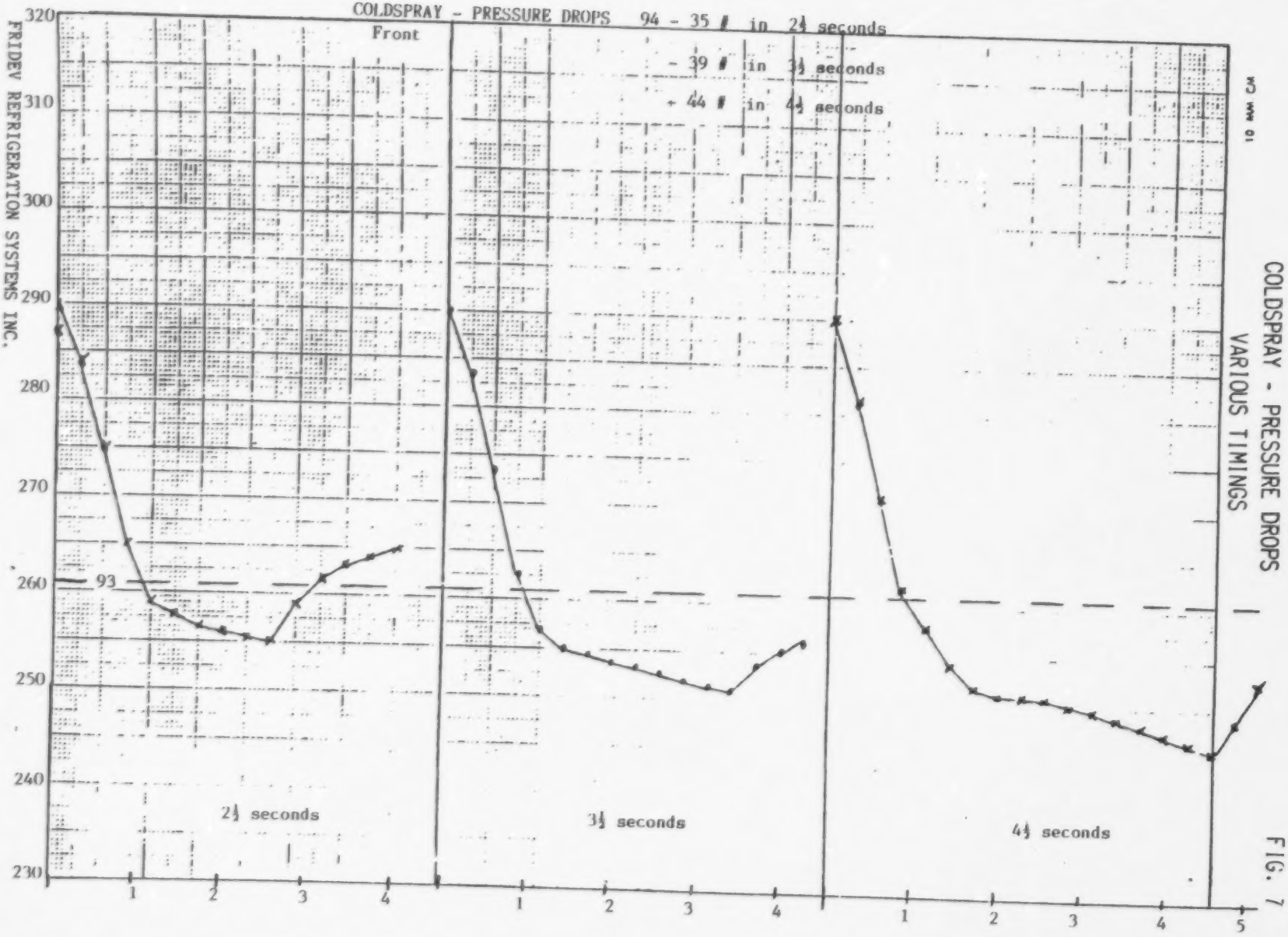

COLDSPRAY - PRESSURE DROPS 94 - 35 # in 2½ seconds
Front
- 39 # in 3½ seconds
- 44 # in 4½ seconds
FRIDEV REFRIGERATION SYSTEMS INC.
320
310
300
290
280
270
260
250
240
230
93
2½ seconds
3½ seconds
4½ seconds
1
2
3
4
1
2
3
4
1
2
3
4
5
COLDSPRAY - PRESSURE DROPS
VARIOUS TIMINGS

FIG. 7

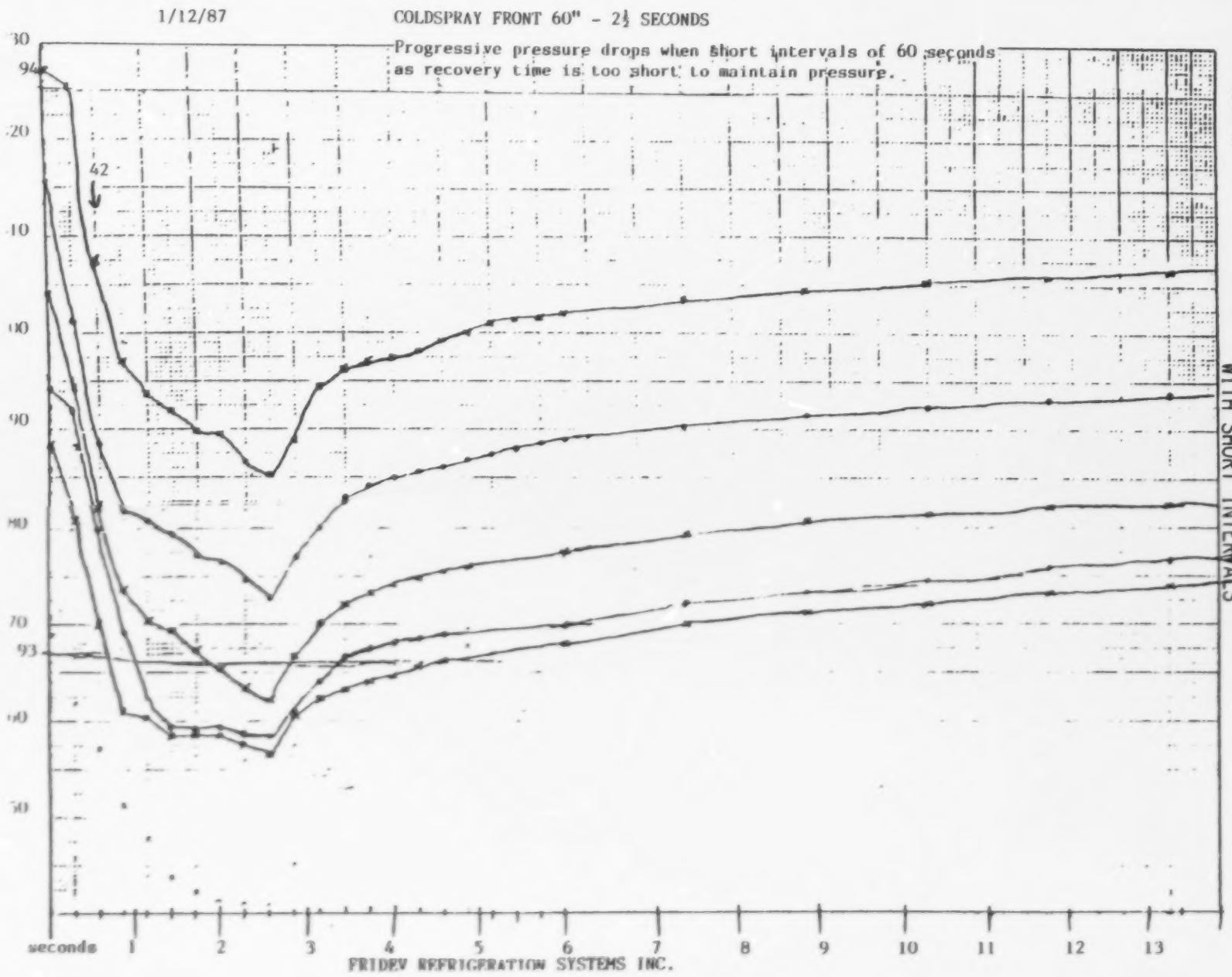



FIG. 8

COLDSPRAY PRESSURE DROPS WITH SHORT INTERVALS

The top section of the walls reacted adequately to the temperature fluctuations created by the Coldsink and Cold-sprays, but the bottom part of the side voids was much more sluggish, regardless of whether the cold was coming from the top or the bottom of the container.

In the floor, air circulation was really hopeless. Not only did the wooden blocks that had been placed above the insulation effectively slow down the air circulation, but there was practically no communication between the right wall void and the floor due to poor workmanship. To compound the problem, the copper pipes that had been placed in the floor to test a heating system were partially blocking whatever air circulation could have been created in the floor.

Everything conceivable was tried to correct the situation. The Coldsink vent in the floor was replaced by a Coldspray, the opening to release the pressure in the void was moved around in the floor and in the doors, but nothing seemed to improve the air circulation in the floor and at the base of the walls. It was then agreed that the design of the floor void was obviously totally inadequate for the purpose of the system to be tested, and that it should be modified. The partial blocking of the right wall void would also be removed.

## 7. MODIFICATION TO THE CONCEPT (FEBRUARY 1987) AND ROAD PROTOTYPE TESTING

### 7.1 New design for the floor and wall voids

The redesigning had to take into account not only the air circulation in the voids but also their strength and the construction limitations of the container as it was decided that the laboratory prototype should be made roadworthy for testing during the summer.

#### 7.1.1 Rebuilding the floor

The void in the floor had to be strong enough to support the weight of a fork-lift and of a loaded pallet, and permit the unobstructed circulation of air in all directions, particularily towards the sides. By itself, heat coming from the bottom of the container will not migrate to the side unless it is pushed to it. This push does not have to be very strong as long as there are no obstructions to the air flow. Previous tests had demonstrated that the Coldsink Vent was insufficient and that the Coldspray was blocking the air circulation with excess dry snow. The use of a small air blower was finally considered.

Several approaches were considered to improve the air circulation in the floor. After removing the original wooden blocks and covering the insulation with a 2.2cm (7/8") plywood subfloor, to eliminate the irregularities of the polyurethane insulation and reinforce the floor, it was finally agreed to adopt a fish bone design including a 4cm (1.5") deep central duct going from one end to the other of the container, and then short perpendicular ducts 1 m x 30 cm (3 1/2' x 1') to direct the air toward the voids in the side walls, through small holes perforated in the sides of the central duct. (See figure 9). The openings toward each small lateral duct had to be calibrated to evenly balance the flow of air coming from the central duct, so that the amount of air arriving at the base of the wall voids would be uniform. A sheet of 2.2cm (7/8") plywood enclosed the duct work and was covered over with the original aluminum plates.

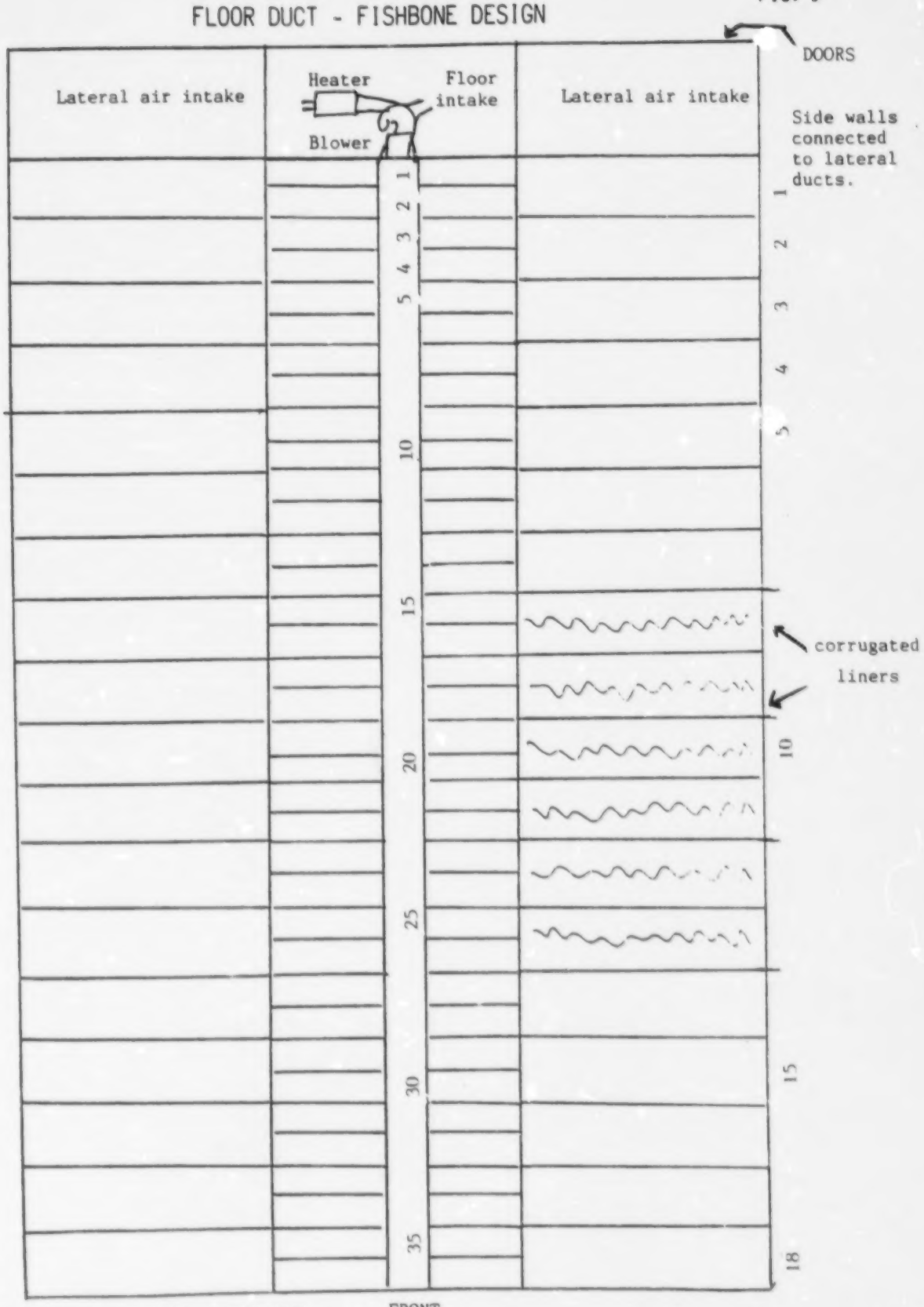
#### 7.1.2 Rebuilding of the walls

The voids in the sides had to be as thick as possible to ensure a good ascendant flow of heat on the insulated side and descendant flow of cold on the cargo side, but unfortunately the space available was limited, as the width of the cargo space must remain as large as possible to facilitate loading and unloading, and the insulation must be as thick as possible to cut down on $CO_2$ consumption. In addition, the walls now had to be able to support the pressures of shifting loads.

In practical applications, the best combination of dimensions would have to be determined for each specific application, as the priority of each factor might be different depending on the

FIG. 9

## FLOOR DUCT - FISHBONE DESIGN

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application; but for the current tests, the construction criteria had to be established to determine the optimum operational solution. Again, several approaches were considered to improve the air circulation in the side voids. After removing the original wooden blocks and covering the insulation with 1.25cm (1/2") plywood to eliminate the irregularities of the polyurethane insulation, it was finally agreed to reduce the thickness of the void to 2.2cm (7/8") but to canalize the air flow inside vertical chimneys 60cm (2') wide, each one being connected to two short ducts in the floor. In doing so, the thickness of the walls was reduced and the air flow in the void was regularized. The walls were closed again with the same 1cm (3/8") plywoood and plastic liners. It was also decided to test a new corrugated fiberglass in the void to facilitate the air circulation inside the cargo space. This type of panel, which is used by CN to patch its insulated containers, is essentially the same type of panel successfully developed by CP to line their intermodal refrigerated containers.

### 7.2 Installing a pneumatic blower in the floor void

To create the stream of air required in the floor void, it was decided to test the use of a small pneumatic blower under the floor, which would blow air inside the central duct which would become a small stabilizing balloon. The air would then go inside the fish-bone ducting system to the wall voids and roof void. The air intake for the blower would be in the wall voids completely in the back of the trailer near where the blower would be located under the floor. This blower would operate without requiring a new source of energy in the system. The air required would come from the $CO_2$ gas at high pressure existing inside the $CO_2$ Reserve Tanks, which would then be reduced to the appropriate pressure of 1.5 bar (20 psi.)

The blower selected, equipped with a small pneumatic motor, delivered a very powerful air supply for its size and consumed little air at low pressure. After testing, it appeared that the air circulation would be adequate.

### 7.3 Installing a diesel heater

As the rebuilding of the floor was in process, it was learned that distributing heat through a glycol radiator system in the floor might not be very safe as the body of a trailer is quite flexible, and that a rupture of the glycol-carrying pipes would cause a messy leakage. Warm air heaters were strongly recommended. These heaters can be operated with gasoline, propane or diesel.
The diesel system was finally adopted because of its excellent performance, small size and low cost.

A small 11,600 kJ (11,000 Btu) Espar diesel unit has enough capacity to warm up the air in the void network and stop the heat from escaping outside the cargo area during the winter months.

It is equipped with a small electric fan to push the hot air out of the heater but this fan would not be powerful enough to push the warm air through the ducting system.

As a pneumatic blower had been installed under the floor, it was now possible to link the two equipment together and to push the warm air efficiently through the void and, at the same time, activate a small alternator to recharge a battery which would feed the small electric fan of the heater and generate the electricity required for the glow of the Diesel heater.

### 7.4 Reinstalling the Coldsprays

It was decided to combine the two Coldsprays in the roof void, and to have only one sensor in the center of the roof void to regulate the dispersion of the dry snow in the front and in the back of the void, at the same time, creating a uniform cooling inside the total envelope. The other automatic Coldspray was then installed inside the cargo area, to permit quick changes in temperatures inside the container, and evaluate how well the heating and cooling systems inside the envelope would react to these changes of temperature.

It was decided that there was no reason to increase the capacity of the Coldsink to handle subzero temperatures inside the cargo when we already knew that the Coldspray injection inside the cargo space could guarantee sub-cool temperatures, and that frozen foods do not object to the presence of $CO_2$ atmosphere or eventual super-cooled temperatures. Consequently, it was now possible to control the inside temperature of the container with the Coldsink only, for the transport of fresh and chilled products, and with a combination of Coldsink and Coldspray for the transport of frozen products.

The manual Coldspray, used for pre-cooling, was connected from the top of the Coldsink to permit a smooth filling of the Coldsink when starting the operation.

### 7.5 Reinstalling the measuring devices

These various modifications meant that we had to relocate all the thermocouples in the floor and in the wall voids. To properly monitor the transfer of cold or heat inside the voids, we placed thermocouples inside the void and directly opposite, on the cargo walls or floor, so that we could measure the differences in temperature. Some of these thermocouples were at the top of the box close to the ceiling, others at the bottom, close to the floor. Some thermocouples were in the central floor duct, others in the lateral ducts. The temperatures of the Coldplate and the Coldsink were monitored in several places along the ceiling. In all, 79 themocouples were located in the container and connected to the Fluke Datalogger.

Pressure transducers in the Reserve tank, at the transfer point

between the Coldsink and the Reserve tank and at the level of the Coldsink vent, were again in position to monitor any pressure fluctuations.

## 7.6 Testing the modified prototype

The modifications were completed by May 10, 1987, and the testing program could resume.
It was agreed that the wheat should not be reloaded inside the container until it was certain that every part of the system was operating properly, considering that it would be practically impossible to make additional modifications if the cargo was reloaded. The tests were consequently carried on inside an empty cargo space, which made it quite demanding on the system, as the temperature of a mass of air is much harder to control accurately than a mass of product, pre-cooled to a specific temperature, placed inside the cargo area.

The following is a description of the various tests conducted. The testing of the Prototype was discontinued on July 22 when it became clear that additional major changes had to be mad

SCHEDULE OF TESTS

| | conditions | freq. | lengt |
|---|---|---|---|
| May 11 | Cargo Coldspray 30°F(4on,50off).Heater 80°F | ev/min | 1hr |
| 12 | Cargo Coldspray 30°F(4on,50off).Heater 80°F | ev/min | 2.5hrs |
| 13 | Pressure data, Coldsink | ev/1/3s | 1hr |
| 15 | Stable Coldsink, cargo Coldspray 30°F | ev/min | 1.5 hr |
| 19 | Testing controls, various adjustment | various | 4hrs |
| 23 | Pressure Regulator, Coldsink | various | 6hrs |
| 26 | Cargo Coldspray 30°F,heater+blower(floor)on | ev/2min | 6hrs |
| 27 | Cargo Coldspray 30°F, floor blower on | ev/2min | 4hrs |
| 29 | Coldsink only, no Coldspray or blower | ev/2min | 2hrs |
| June 2 | Ceiling Coldspray (30°F), cargo blower on | ev/2min | 4hrs |
| 8 | Ceiling Coldspray only, cargo blower on | ev/2min | 2.5hrs |
| 16 | Coldsink,both Coldspray,blower on(30°F) | ev/2min | 5.5hrs |
| 18 | Coldsink,both Coldspray,blower on(15°F) | ev/2min | 2hrs |
| 19 | Adjust Controls, various temperatures | various | 6hrs |
| 23 | Pressure readings, Coldsink | ev/15s | 3.5hrs |
| July 3 | Pressure reading, sensitivity+flow valve | ev/3s | 6hrs |
| 6 | Coldsink 295#, cargo Coldspray (20°F) | ev/2min | 2hrs |
| 7 | Coldsink 260# only, blower on | ev/2min | 3hrs |
| 8 | Pressure readings, Coldsink and Reserve | ev/3s | 2hrs |
| 14 | Coldsink only (260#), blower active | ev/2min | 6hrs |
| 21 | Coldsink only (260#), blower active | ev/2min | 5hrs |

### 7.6.1 Tests on Air Circulation in the Voids

Again, the results were very disappointing. The air circulated by the pneumatic blower located in the central duct, was not moving fast enough through the system to compensate for heat penetration from the outside. Consequently, there was a progressive warming up of the floor, as it was impossible to cool the floor down to the desired temperature by circulating the cold air coming from the Coldsink through the duct system in the floor.

Conversely, when we put the diesel heater on, we very quickly had a very hot central duct, then a progressively warmer lateral duct system, but not enough heat was transfered to the wall voids to insure the protection of the load from the outside cold.

All in all, the heat transfer through the ducting system as very sluggish and definitely inadequate. The thermocouples placed against the walls and the floor, but inside the cargo space, were not measurably affected by the fluctuation of the void temperature, which meant that the heat transfer from the void area to the cargo area, protecting the cargo, was not functioning with any efficiency, and that, consequently, all our efforts to design a system of indirect jacketed protection were inconclusive if not worthless.

### 7.6.2 Tests on cooling with the Coldsink-Coldplate

While difficulties were experienced with the void-cooling system, the qualities of the Coldsink-Coldplate approach in the roof, combined with the air turbulence created inside the cargo area, became more and more noticeable. It became clear that the cold from the Coldplate was transfered uniformly to the cargo area, and that the heat from the cargo area was transferred upwards towards the ceiling, where it was absorbed by the Coldplate.

But at the same time, it was noted that the efficiency of the Coldsink-Coldplate was hardly what should have been expected. We discovered that the temperature of the liquid $CO_2$ circulating inside the Coldsink piping had to be much lower that the calculations had indicated, to maintain the Coldplate at the desired temperature. This was because of a poor thermal transfer between the piping and the plate, caused by a very poor mechanical connection between the two components. This had been anticipated, but not to the extent experienced.

This was very easily noticeable on the ceiling of the container where plaques of frost could be seen where good contact existed, and nothing at all when the pipe did not touch the aluminum plate. At the same time, we noticed that the internal ventilation inside the cargo space was compensating for the weakness of the void system. Any heat in the voids, which was progressively passing through the inside liner, was being pushed inmediately towards the ceiling by the internal ventilation. When it reached the ceiling, this heat was immediately absorbed by the Coldsink-Coldplate unit.

It was known that ventilation was needed to dispose of the heat generated by the respiration of most fresh produce, but we were far from realizing that this internal ventilation, as small as it was, would have such a capacity to move the heat towards the Coldsink-Coldplate.

It became more and more apparent that this combination of inside air turbulence and Coldsink-Coldplate would be the solution to replace the previous 'jacketed' approach.

7.6.3 Tests on the Pressure Drop in the $CO_2$ Reserve tank

It was also known that the various pneumatic controls used were consuming a small amount of $CO_2$ gas, but this was of little consequence as the liquid in the Reserve Tank was always warming up a little, in spite of the insulation.

It was known that as the Coldsprays and Coldsink were consuming liquid $CO_2$, this was progressively reducing the pressure of the liquid inside the $CO_2$ Reserve tank, as the tank was of a limited capacity and totally independent of any new pressure source until it was refilled.

The decrease in pressure resulted from the frequency with which the Coldsprays or Coldsink vents had to be activated to fight heat infiltration. The extent of this decrease had already been calculated.

Now that gas was taken out of the $CO_2$ Reserve tank to power the small blower in the floor or the blower inside the cargo area, the pressure drop became very fast and very high, reducing the temperature of the liquid $CO_2$ inside the Reserve tank to a level that was much lower than the one required to operate the Coldsink adequately.

Tests were conducted in order to repressurize the $CO_2$ Reserve tank with $CO_2$ gas coming out of the Coldsink Vent. The results appeared promising.

7.6.4 Tests on the filling and closing of the Coldsink

For the Coldsink to be efficient and to accomplish its function without straining, it had to be filled up with liquid $CO_2$. As the temperature of liquid $CO_2$ rises, its pressure rises accordingly, while some of the liquid $CO_2$ converts to gas. When the pressure reaches a pre-set point, the Coldsink vent opens and lets $CO_2$ gas escape, which brings the pressure and the temperature back to the desired level. If the Coldsink is empty, the system does not cool anymore. If the Coldsink is too full, the liquid $CO_2$ escapes through the Coldsink vent and creates dry snow. This cools the atmosphere more than required and increases the consumption of $CO_2$ unnecessarily. The refilling of the Coldsink and the closing of the vent at the appropriate time became a major aspect of the testing and research program, so that the system could remain operational and economical for long periods of time.

The concept of the refrigeration system assumes that the temperature, and, consequently, the pressure of the Coldsink must be independent of the temperature, and consequently, the pressure of the $CO_2$ Reserve tank. The Coldsink vent will always open at a pre-set pressure, but if the pressure of the $CO_2$ Reserve tank goes down steadily when the process continues, problems will develop.

Eventually, the pressure of the $CO_2$ Reserve tank will become very low, and the pressure differential between the Coldsink and the $CO_2$ Reserve tank will be such that the transfer of liquid will become insufficient for the Coldsink to remain completely filled up or even impossible, if the pressure in the Coldsink cannot reach the $CO_2$ Reserve tank pressure before the Coldsink vent closes.

The consequences of this problem are that the Coldsink progressively empties itself, warms up, and consequently loses its power of heat absorption through the Coldplate. The lack of filling or the partial filling of the Coldsink can also result from the fact that the inclination of the container makes it impossible for the liquid $CO_2$ to completely fill the Coldsink, but this situation is corrected as soon as the Coldsink returns to the horizontal.

The problem in refilling came from the resistance in the piping system, which made it difficult to respond quickly to a pressure drop between the vent and the refilling point of the $CO_2$ system. With the existing design of the Coldsink, when the pressure in the $CO_2$ Reserve tank drops to a pressure of about 10 bars (150 psi) lower than the set pressure of the Coldsink, the pressure differential is such that there is not enough time to refill the Coldsink before the Coldsink vent closing pressure is reached and stops the process. After a while, the Coldsink empties completely and becomes totally non-operational until it is refilled with liquid $CO_2$.

Similarly, if the pressure differential is small between the preset pressure of the Coldsink and the pressure of the $CO_2$ Reserve tank, it becomes very difficult to ensure that the Coldsink does not overfill before the Coldsink vent closes. Quite a long time was spent in developing the appropriate control to regulate the filling of the Coldsink, and the closing of the Coldsink vent at the appropriate time.

Although these prblems were detected in mid-June, it was only in mid-August, 1987 that the solutions necessary to make the system truly operational were developed.

## 7.7 Analysis of the test results and interpretation

Three obvious conclusions were drown from the battery of tests:

- the jacketed approach had to be dropped
- a good inside ventilation had to be developed
- the heat absorption capacity of the Coldsink-Coldplate had to be increased.

### 7.7.1 The jacketed approach is unacceptable

The concept of creating a cold or hot void all around a load is good, but is not practical for road transport because there is not enough space or volume available on road vehicles to make it work properly. The jacketed principle would be excellent if it were possible to create an appropriate air circulation around a load, but in transport vehicles, space is at a premium, particularly along the walls, as shippers want to load their vehicles (trailer, container or wagon) with two 40x48" pallets side by side. Consequently, every inch taken off the width of a vehicle is better used in improving the insulation than in creating a void.

In the floor, the air circulation had to be restricted to a mere 3.8cm (1.5") void, and, here again, whatever space is available would be better used by increasing the quality of the insulation than to try to create a horizontal air flow. It was consequently decided that the voids in the floor and in the walls should be eliminated.

The fact of eliminating the void in the floor made it mandatory to relocate the Coldsink vent and to remove the small blower. The concept of a heater working in the floor void had to be replaced by a standard heater inside the cargo space.

The Coldsink vent, while located in the floor, had demonstrated its limited capacity to cool down the air, as the $CO_2$ gas expelled from the Coldsink had already lost most of its Btu content; but the pressure of the vapours being vented is very high, and represents a potential source of energy which should not be wasted, but recovered and put to work.

It was consequently decided to harness it to power the cargo pneumatic blower used to bring any heat generated towards the Coldsink-Coldplate unit faster.

### 7.7.2 The inside air turbulence is of prime importance

The ventilation inside the cargo area does not pretend to transfer cold from a refrigeration unit in the nose of a vehicle all the way to the back door, but only to create a lateral turbulence, from the center of the ceiling down to the cargo below, then apart towards the walls, and then all the way up to the Coldsink-Coldplate which will absorb the heat that has been collected during this short cycle.

This lateral turbulence must be repeated as often as possible along the center line of the ceiling, so that no corner of the cargo space remains unaffected.

If the walls of the cargo space are lined with a corrugated material, the return air flow to the ceiling will be facilitated, and if any warm air infiltrates through the insulation, it will be moved towards the Coldsink-Coldplate before it has the time to affect the cargo.

Similarily, for the floor, it is important to create an air flow which will sweep this air turbulence towards the blower intake.

7.7.3 The Coldsink-Coldplate must be improved

As the amount of heat rising toward the Coldsink was increa-sed, it became imperative to increase the heat absorption capacity of the prototype's ceiling. It became clear at that time that, with the present configuration, any additional heat might well overstrain the system's heat absorption capabilities, and invalidate the test results.

## 8. MODIFICATION OF THE CONCEPT (JULY 15, 1987) AND TESTING OF THE ROAD PROTOTYPE

By July 15th, it was well established that something had to be done to improve the performance of the prototype, as it was inconceivable to put the present configuration on the road. It was decided to strip and rebuild the container once more. The modifications were completed by August 3, and the prototype was immediately placed on a container chassis and taken outside for testing in the heat and sunshine.

### 8.1 Removing the void in the floor

The floor was reopened, all the duct network, the blower, the Coldsink vent, the heater and all the thermocouples were removed. A standard aluminum T flooring recovered from an old, scrapped, insulated container was then installed, and the thermocouples were replaced in the floor grooves, and here and there inside the cargo space.

The voids on the walls should also have been removed, but it was felt that the cost involved would not justify the benefits to be gained, since the problem was not as serious in the walls as in the floor, and since the walls communicated with the ceiling void anyway. Of course, it was known that the wall voids would be hard to cool but we also knew that they were in fact acting as insulation. As long as there was not a full-length corrugated siding inside the container, it was felt that this void would act as an additional protection against direct heat penetrating from the outside.

### 8.2 Installing a pneumatic blower inside the cargo space

As the results from the small blower in the floor appeared very encouraging, it was decided to test the use of a pneumatic blower inside the cargo area, but, this time, to create a gentle transverse air turbulence all along the ceiling of the container. By installing a metallic duct system, directly attached to the Coldplate, which would project cold air down toward the cargo through small openings strategically located, it was felt that any heat generated by the respiration of fresh produce could be displaced, and would accelerate the rise of warm air toward the ceiling to be absorbed by the Coldplate-Coldsink.

As the distance to sweep was very limited (maximum 8') and as the purpose was not to push cold air all along the roof or the floor of a 45' trailer like a mechanical unit, but only to create a turbulence, it was felt that a small pneumatic blower with a 2.75 bars (40 psi) rating would do the job adequately. This blower was placed in the nose of the trailer and the ceiling duct was properly calibrated to disperse the air turbulence all over the cargo area.

Testing of the container had clearly demonstrated that maintaining the pressure in the Reserve tank was paramount and that it was not acceptable to reduce it even further by using the gas in the Reserve tank to operate a pneumatic blower, as we had been doing for the blower in the floor.

It had been found that the gas coming out of the Coldsink vent did not have much cooling power, but it was ejected from the Coldsink at a pressure around 20 bars (300 psi). If it was possible to recuperate this pressurized gas and store it temporarily, there might be enough energy developed to activate the blower with no additional energy source and no additional consumption of $CO_2$. All that had to be ascertained was that the pressure of the temporary $CO_2$ gas storage would not interfere with the normal operation of the Coldsink vent.
It was established that this pressure had to be lower or equal to the pressure at which the Coldsink vent would close. If the Coldsink vent expelled more gas than could be stored in the temporary gas storage, this gas would have to be blown off. It then became a matter of properly balancing the size of a temporary gas storage to the quantity of gas expelled from the Coldsink vent, with the quantity of gas required by the blower at a much lower pressure.

## 8.3 Improving the heat absorption capacity of the Coldsink-Coldplate

Considering the difficulties originally encountered in installing the Coldsink-Coldplate in the roof, and the poor connection between the copper pipes and the aluminium plates, several approaches were considered to improve the construction of the Coldsink without having to scrap it completely.

A study of the heat absorption capability of finned piping was subcontracted with Brian Mori, and it was finally agreed to increase the heat absorption capacity of the existing Coldsink, by adding two 40-feet finned pipes inside the void of the roof. (see figure 10). The frosting of the finned piping was greatly reduced, because of the concentration of $CO_2$ inside the roof void which absorbed the humidity in the atmosphere. This finned piping was made of 2.2cm (7/8) copper piping covered with an aluminum fin, rolled 3 fins per cm (7 fins per inch), and which had a heat absorption surface 2 1/2 times the outside surface of the pipe.

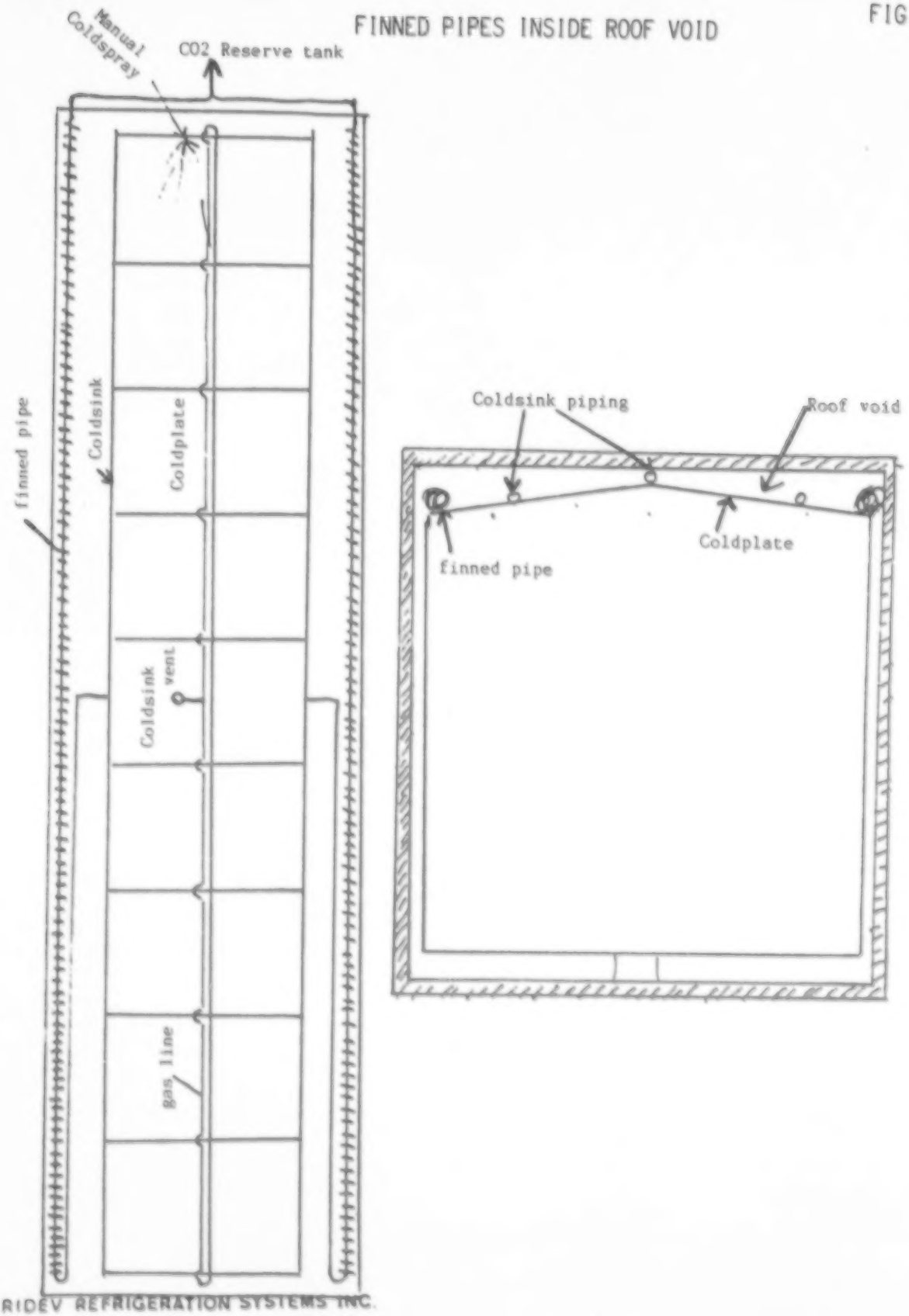
This innovation improved the heat absorption of the Coldsink, but did not help with the Coldsink refilling, as, in effect, the overall friction inside the system had been increased as well as the length of pipe.

## 8.4 Reinstalling the measuring devices

All the thermocouples had to be repositioned; but, since the thermocouples from the floor void were now available, it was now possible to position them extensively inside the cargo area, in

FIG. 10

# FINNED PIPES INSIDE ROOF VOID

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places where it was felt additional data should be gathered. The Fluke Datalogger made it possible to scan all these channels at regular intervals, or, on request, to monitor the fluctuating temperatures at any one point and at a frequency of 3 readings per second.

## 8.5 New tests on the rebuilt prototype

The new testing program started on August 3. It was agreed at the beginning not to load the container with the wheat already used for cargo during the previous tests, in case more problems were experienced with the system. After 3 tests in which everything seemed to be working properly, it was decided to run a series of tests of long duration (3-4 days). Out of the existing 79 thermocouples, 30 channels were selected as being particularly significant. This gave the possibility of recording events, on a frequent and regular basis, for long periods of time (up to 4 days). These readings were recorded on the magnetic tape, inside the Fluke, and later unloaded into the Toshiba, and processed.

Since the tests showed the system was working effectively, it was decided to reload the prototype on August 16 and start cooling down the load to 0°C. The load was then maintained at this temperature for almost two weeks, despite very high outside temperatures. The control equipment confirmed that the proper temperature was maintained in the cargo area. During this period, new techniques for interpreting the data were developed which gave much greater flexibility, and better interpretations of the existing data.

By September 23, specific tests were conducted to check the uniformity of cooling of the Coldsink-Coldplate, the pressure drops inside the system, and the automatic refilling of the Coldsink.

SCHEDULE OF TESTS - FROM - 3/8 TO 24/9, 1987

| | condition | frequency | length |
|---|---|---|---|
| Aug 3 | Pressure readings, Coldsink and Reserve | various | 4hrs |
| 5 | Coldsink 260# (4"on, 50"off), blower active | ev/3min | 20hrs |
| 12 | Pressure readings, Coldsink ventings | various | 6hrs |
| 13 | Coldsink 255#, Coldspray void 30°F | ev/3min | 8hrs |
| 14 | Coldsink 260#, Coldspray void 25°F | ev/3min | 22hrs |
| 16 | Pressure testing, Coldsink vent | various | 6hrs |
| 17 | Load wheat, all working(30°F), no Fluke | various | 7days |
| 25 | All working (30°F) with Fluke | various | 5days |
| Sep 3 | Cargo Coldspray only (30°F) | ev/5min | 17hrs |
| 4-7 | Coldsink 265/280#, Coldspray 30°F | ev/5min | 17hrs |
| 8-9 | Coldsink 265#, Coldspray 22°F (4"on, 50"off) | ev/5min | 48hrs |
| 10 | Coldsink 285#, Coldspray 22°F " | ev/5min | 23hrs |
| 15 | Coldsink 275#, Coldspray 27°F " | ev/5min | 45hrs |
| 23 | Coldsink 275#, Coldspray 27°F " | ev/5min | 16hrs |

By Sept 24, the needed information had been gathered, and the wheat was returned to Ste-Rosalie in excellent condition as it had been protected against any contamination by the $CO_2$ gas.

## 8.6 Results of Cooling Tests

When the Coldsink was filled up with liquid $CO_2$, the heat absorption was now excellent, as the finned pipes tended to compensate for some of the poor contact between the pipes and plates. At each venting, the piping was brought back to the set temperature level which had been selected, and the temperature of the plates remained very uniform. But, as forseen, after placing the fin pipes in place, the problems with the Coldsink refilling were now compounded by the 25 meters (80 feet) increased length of the Coldsink network. Because of this, the pressure differential between the Coldsink vent and the refilling point of the Coldsink was even greater than before, and when the pressure in the Reserve tank dropped below 10 bars (150 psi), refilling became impossible.

As the Coldsink emptied, the temperature of the Coldplate rose and lost part of its heat absorption capacity. Fortunately, as soon as the Coldplate warmed up above the temperature required for proper heat absorption, the Coldspray in the void of the ceiling was activated, and sent short bursts of dry snow onto the Coldsink-Coldplate unit. This very quickly brought the temperature of the plate back to the proper, preset temperature, as determined by the nature of the cargo.

## 8.7 Results of ventilation tests in the prototype

The ventilation produced by the interior blower was excellent, as long as there were regular ventings of the Coldsink or, in other words, as long as the Coldsink was filled up. Proper operation was essentially a matter of calibrating the size of the temporary gas storage to the expected quantity of gas to be vented. When the Coldsink started to empty, ventings became much more irregular and erratic. The venting was either insufficient or much too great, depending on how long the vent had to remain open to obtain a refilling. When the Coldsink became unable to refill on its own and had to depend on the Coldspray to operate, the venting was totally insufficient. Thus, if the cargo had a tendency to warm up, the use of the Coldspray to replace the Coldsink would have to be considered only as a back-up in an accidental or emergency situation, not as a regular cooling technique.

## 8.8 Tests to control the pressure inside the Reserve tank

Now that the gas inside the Reserve tank was not used to operate the blower, the drop in pressure had returned to its normal level. But this pressure drop still existed and created a problem in the transfer of liquid from the Reserve tank to the Coldsink

when the pressure became too low. This is compounded if the Coldsink pressure control is set at a very high pressure.

## 8.9 Solutions to the various problems

By the end of the testing period, the various problems were very clearly identified, and a solution was elaborated which would permit the development of the final concept. This solution was disclosed at the advisory committee meeting on October 7, 1987, and included the schematic process description of the proposed system, and a preliminary piping and instrument diagram.

The new concept was fully developed during the following months by Fridev's team of engineers, assisted by scientists from McGill University.

## PART III - THE SYSTEM DEVELOPED AND ITS APPLICATION TO THE TRANSPORT OF FRESH BEEF CARCASSES

### 9. THE "HEART AND LUNG" CONCEPT

#### 9.1 The new heat absorption system

The Cryogenic $CO_2$ refrigeration system is based on a heat absorption process essentially accomplished by natural convection. The heat from outside which penetrates inside the cargo space through the insulation or the heat which is generated inside by the product is absorbed by a Coldplate which covers the entire ceiling. The natural convection effect is helped by a light, transversal air turbulence generated close to the floor on both sides of the insulated vehicle; this ensures a quick transfer of the heat toward the ceiling.

When the heat reaches the Coldplate, it is transferred by conduction to the Coldsink on which the Coldplate is attached. The Coldsink is made of a series of parallel extruded aluminum pipes which are filled with liquid $CO_2$. The liquid $CO_2$ is maintained at a predetermined pressure, established according to the heat absorption requirement of the Coldplate to maintain the cargo at a preset temperature. The predetermined pressure varies and adjusts automatically the heat absorption capability of the Coldplate. The insulation on the roof of the vehicle is as thick and efficient as possible to cut down heat infiltration from the outside, close to the Coldsink, which would result in activating it without reason or purpose. The floor is cooled down by the gas $CO_2$ evacuated from the Coldsink. The insulation on the floor of the vehicle is as thick and efficient as practical to limit the amount of heat generated under the cargo, as it is always a rather difficult place to remove heat infiltration.

The insulation on the sides, front and door will dictate the consumption of liquid $CO_2$, but will also dictate the amount of air turbulence generated by the system. For example, if the vehicle is poorly insulated, a lot of outside heat will penetrate inside the cargo space and it will automatically generate a lot of evaporation of liquid $CO_2$ - and, consequently, a high consumption of fuel; but, as a direct consequence, it will increase appreciably the air turbulence inside the cargo space to push the heat quickly toward the ceiling, and maintain a stable temperature inside. Similarly, if the cargo generates a lot of heat, such as is the case with fresh leafy vegetables, it will increase the air turbulence which will dislodge the heat from the cargo.

This evaporation of liquid $CO_2$ and creation of gas $CO_2$ will happen as long as there is liquid $CO_2$ available inside the Coldsink to be evaporated when the liquid warms up, because it has absorbed the

heat inside the cargo space as it is transferred from the Coldplate to the Coldsink.

Pipes filled with liquid $CO_2$ are connected by return gas lines connected to the extremities of the Coldsink inside the insulation of the roof of the vehicule to form a closed loop. When the vehicle is on an inclined road, part of the liquid $CO_2$ will temporarily slide inside the return gas lines (which are the lowest) coming from the opposite part of the Coldsink pipes (which are then higher). When the vehicle is back on a flat road the liquid $CO_2$ will return right back in the Coldsink pipes and resume the cooling of the Coldplate in this area. This motion of the liquid $CO_2$ back and forth inside the Coldsink pipes permits an exellent evacuation of the gas which could be trapped inside the Coldsink pipes, and permits the regular defrosting of the Coldplate. The possible condensate waters are then directed toward the floor of the vehicule by plastic PVC drip pans attached to the lowest parts of the Coldplates.

The stability in temperature inside the vehicle is ensured by an automatic adjustment of the pressure of the liquid $CO_2$ inside the Coldsink whenever there is a fluctuation of the temperature inside the cargo area.

As part of the liquid $CO_2$ vaporizes when it is heated by the heat on the Coldplates, the total pressure inside the system increases. When some of the gas is released by opening a vent at the top of the Coldsink, the pressure inside the system returns to the pressure which has been selected for the liquid $CO_2$ to have the adequate heat absorption capacity, to maintain the proper cooling effect.

The regulation of the spread between the pressure level of the vent opening, compared to the pressure level of liquid $CO_2$ in the Coldsink, as well as the actual setting level of the pressure inside the Coldsink, is what will regulate what is called the "Lung" function or "Breathing Rhythm" of the system and the "Heart" function, or "Blood Pressure" of the system.

The "Blood Pressure" has to be very low and the "Breathing Rhythm" very high when the system operates at maximum capacity; conversely, the "Blood Pressure" has to be very high and the "Breathing Rhythm" very low when the system operates at minimum capacity.

## 9.2 The controls of the "Heart and Lung" functions

These two functions are regulated by the appropriate opening and closing of electro-pneumatic valves which receive their instruction from an electronic card which has been designed and programmed to interpret the information received from temperature and pressure captors and liquid level switches.

The heat absorption capacity required of the Coldsink-Coldplate is determined by the difference in temperature which has to exist

between the temperature of the liquid in the Coldsink and the temperature sensors which are located in the front and in the back of the cargo space.

The presetting of the minimum pressure level in the Coldsink and the presetting of the maximum pressure level in the Reserve tank are automatically set as a specific percentage of the maximum pressure level in the Coldsink, and in relation to whatever this level is. This makes it possible to establish the pressure spread which must exist between these various pressures to guarantee a steady "breathing rhythm" and an appropriate "blood pressure" for the system to fulfill its job adequately.

## 9.3 The purpose of the "Breathing Rhythm"

A steady "Breathing Rhythm" will ensure a stable air turbulence inside the cargo space, which has to be adjusted to the heat absorption needs.

This is obtained by calibrating the Coldsink vent valve according to the amount of gas $CO_2$ which has to be evacuated from the Coldsink. If this amount is very small, the Coldsink vent valve will also be very small. If the amount is substantial, the valve will be much larger.

The evacuated gas $CO_2$ supplies a small pneumatic motor. This pneumatic motor, depending on the pressure delivered to it, will activate one or two air blowers. These blowers circulate the air taken at the top front of the cargo box and send it back as an air turbulence inside the cargo box through two ducts located on either side of the box, close to the floor, all along the base of the walls.

The more gas $CO_2$ is generated, the more air turbulence will be created inside the cargo box to quickly send the heat toward the ceiling so it does not affect the temperature of the cargo.

## 9.4 The importance of the "Blood Pressure"

The pressure in the liquid $CO_2$ Reserve tank has to be maintained at a steady pressure in direct relation to the pressure of the Coldsink, to ensure that the refilling process is done as regularly as possible and without excessive pressure drops. This is why a precise pressure relation has been developed between the two components. The controls will always work to bring the pressure relation back to what it should be. As the amount of kilojoule (Btu) obtained from a Kilogram (pound) of liquid $CO_2$ decreases rather quickly when the pressure increases, and the cost of manufacturing also increases tremendously for a high pressure system, it has been felt that the Reserve tank should never be allowed to operate at a pressure higher than 20 bars (300 psi).

## 9.5 The heating System

When the outside temperature oscillates around the freezing point, it is important for the system to be able to switch from a cooling to a heating position without human intervention. This is realized with a small diesel heater which is operated directly in line with the ventilation system described previously. An outside sensor measures the temperature outside and is able to give instructions to the control system when it is appropriate to switch to the heating position, whenever there is a need for heating rather than cooling. In such a case, the liquid $CO_2$ stored in the Reserve tank continues to supply the necessary energy to operate one blower and to recharge the battery which procures the necessary electric current to operate the diesel heater and the electronic controls.

This mode of operation can also occasionally be used to heat the cargo space when the vehicle is separated from the tractor, or when the tractor is stopped for a short while. But whenever the temperature outside is definitely below the freezing point, and when refrigeration will not be used for a while, it is expected that the electricity needed to operate the diesel heater and one of the blowers will be supplied directly by the alternator of the tractor, as the power demand is not excessive and it would to be expensive to burn liquid $CO_2$ only to supply electric power to the system, instead of the prime objective of operating a Cryogenic Refrigeration system.

## 9.6 The electronic controls

For a long time, every effort was make to keep the control system fully pneumatic, so that it could be said that no energy in addition to liquid $CO_2$ was required to operate the Cryogenic Refrigeration system. But, not only are pneumatic controls expensive, they are also extremely difficult to adjust with precision by unskilled labor, and precise adjustments can eventually be disturbed by excessive vibration.

Consequently, it was reluctantly decided to look at electronic controls to direct the operation of the pneumatic valves. This decision was made easier considering recent developments in the quality of electronic components. All-weather components, mostly developed for the military and for the aerospace industry, are now available, and even if they are more expensive, they provide the kind of dependability required for this type of application. A well designed electronic control card permits a lot of flexibility in the development of a system which can react with the precision required for perfect response.

The power supply is of no concern, as the controls have a very small electric demand; a good dependable alternator (to keep the battery in top shape) is standard equipment. This alternator is also powered by the pneumatic motor which drives the air blowers.

## 9.7 Pre-chilling, re-chilling and sub-freezing

The Coldspray technique is now used only for pre-chilling, re-chilling and sub-freezing when quick or extreme cold is required. The Coldspray operates manually and automatically.

For pre-cooling, it reduces considerably the time required in comparison with a mechanical unit.

For re-chilling it is able to re-establish very quickly the right temperature after the opening of doors. The small amount of $CO_2$ required does not increase the concentration of $CO_2$ to an extent which will affect the most sensitive products. For some products, it might even be desirable to have an automatic spraying of $CO_2$ to maintain a low concentration of $CO_2$ inside the box to retard the growth of bacteria.

For the transport of sub-frozen products when temperatures outside are extremely high, it is better to inject some $CO_2$ than to develop a Coldsink-Coldplate system which has a heat absorption capacity so powerful that it is too efficient for most other products which are not sub-frozen. This would force raising the pressure of the Coldsink much too high when the outside temperature is rather cool, which would not be desirable or energy efficient.

## 9.8 The computor simulation model

After the complete system was designed, and the various components selected, it was agreed to develop a simulation model which would include all the unsteady operations of the refrigeration system and would demonstrate that the system could provide a quasi-steady refrigeration and ventilation result.

The program was also required to provide a selection of size for the various valves to be used to ensure an adequate transfer of liquid and gas. All these valves could then be equipped with calibrators to refine the exactitude of the appropriate transfers. To develop the program of this relatively unstable system, Neil Hookey, a post-graduate student at McGill University, specialized in engineering simulation in the heat transfer field, was subcontracted.

The simulation program follows very closely every step of the concept developed. It simulates operations with great accuracy at various time intervals, to demonstrate that the system will be stable and maintain predetermined temperatures as long as there is $CO_2$ fuel in the Reserve tanks.

All the readings have been taken for the first 120 seconds, then one hour later, between 3480 and 3600 seconds, and finally 2 hours later, between 7080 and 7200 seconds. They could have been taken for any time increments, and the results would be the same. (See figures 11, 12, 13)

9.8.1 Testing runs

Tests have been conducted in changing the U Factor of the trailer or in changing the heat absorption requirement of the load. Changes of parameters indicate how the system operates in various situations.

- In the first test run, only one small vent is opened as the heat transfer is moderate, and little $CO_2$ gas is generated. (See figure 14)
- In the second test, 2 small vents are opened as the heat transfer increased considerably, to simulate a high Dt requiring high heat absorption. (See figure 15)
- In the third test, the greatest heat transfer is simulated as if warm beef carcasses had been loaded on the trailer, and extra large heat absorption was required. In such a case, the four small vents are opened. (See figure 16)

9.8.2 Use of the simulation model

The objective of the simulation model is to calibrate the whole system, so that no $CO_2$ gas is lost and that air turbulence is as continous as possible, but calibrated according to the need generated by the amount of heat absorption required. The system has been made stable by selecting a set of fixed parameters for the various elements of the system which perfectly balance all the unstable reactions. It has been possible to modulate the air turbulence by selecting the appropriate valve sizes according to the sizes of the temporary gas tanks, and to the availability of $CO_2$ gas to feed the pneumatic motor.

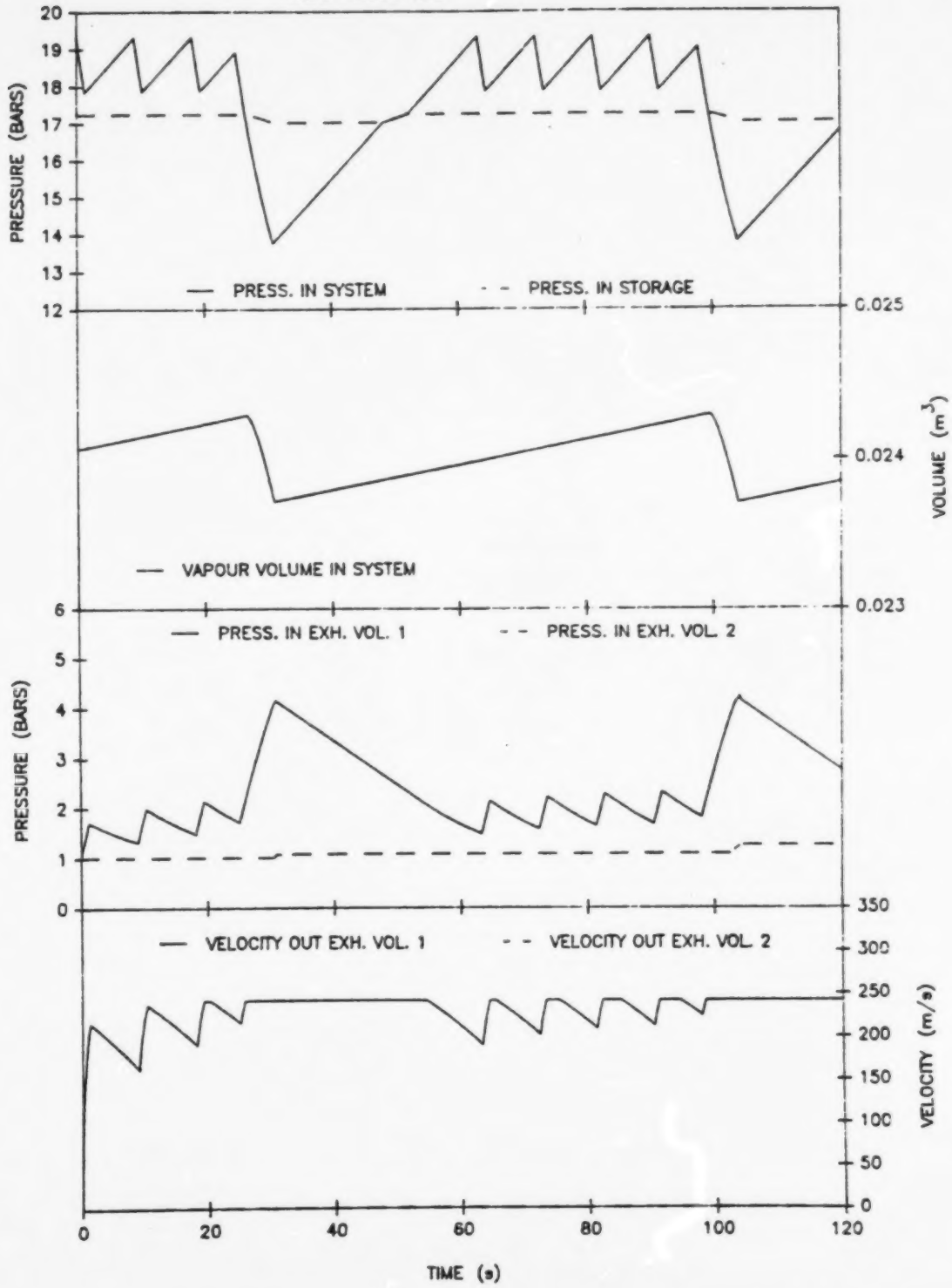
Every test that was conducted confirmed the flexibility of the system, and the great stability of the Coldsink pressure.
Then, by adjusting the various variables such as inside temperatures, U factors, Dt, maximum and minimum pressure spread inside the Coldsink, maximum pressure in the Reserve tank compared to maximum pressure in the Coldsink, it became possible to adjust the average temperature of the Coldsink and, consequently, its heat absorption capability, which is the key to the sound operation of the system.
All these adjustments are automatically dictated by the electronic controls of the microprocessor, which reacts according to the pressure captor and temperatures sensors.

## 9.9 Conclusion

This new concept remains extremely simple and does not include sensitive parts prone to failure or high maintenance. It will maintain inside temperatures at a very stable level which can vary without modification from -30°C to 5°C. It has enough air turbulence to eliminate persistent warm spots without inflicting an excessively dehydrating high air flow on the perishable fresh products. It does not take any room away from the cargo space, except that, naturally, the better the quality of the insulation in the vehicle, the more efficient the system will be.
The only concern about the system at this stage is the weight

FIG. 11

SIMULATION MODEL
120 SECONDS

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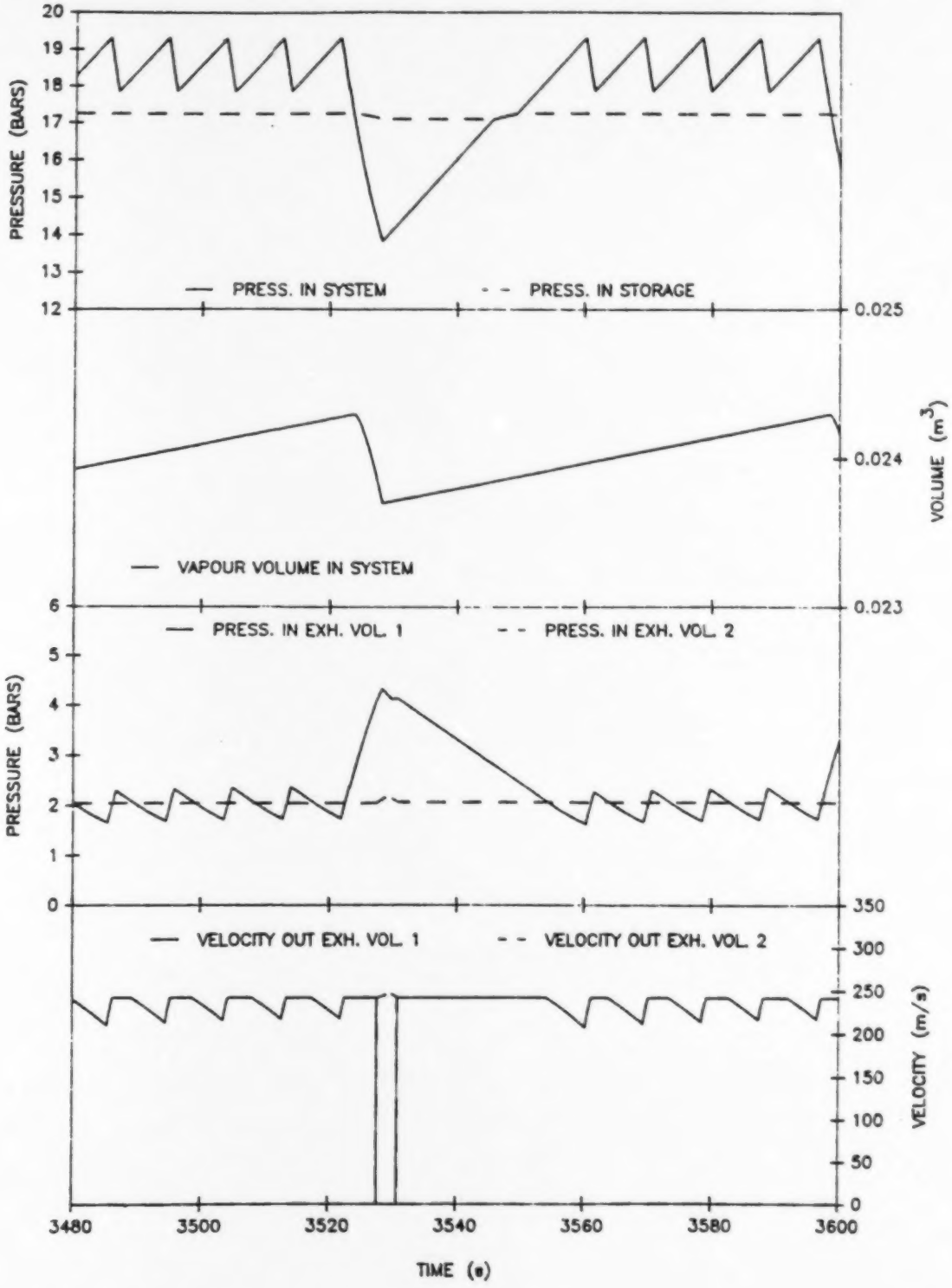
Q150 V201

FIG. 12

SIMULATION MODEL
3600 SECONDS

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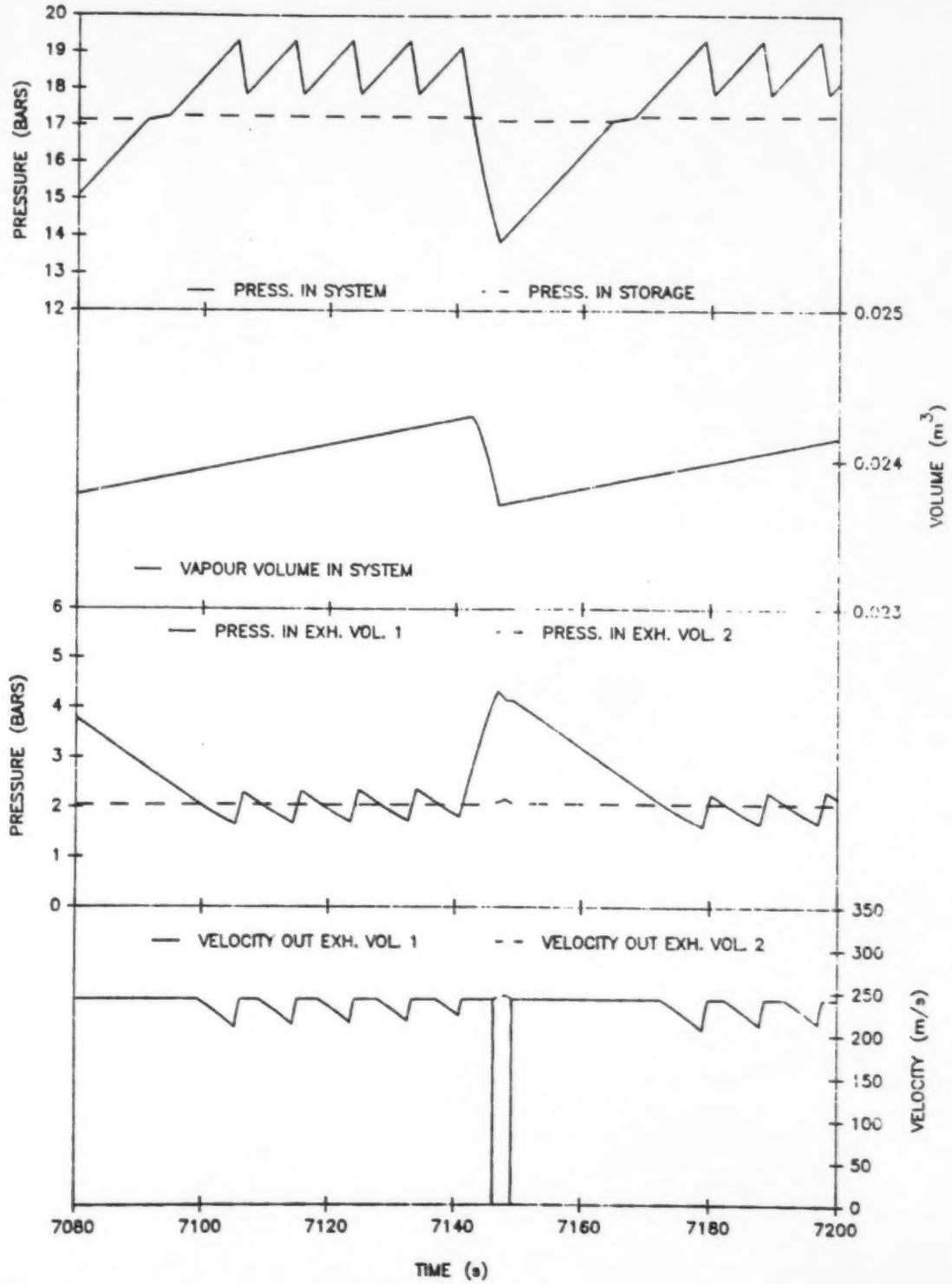
Q150V202

FIG. 13

SIMULATION MODEL
7200 SECONDS

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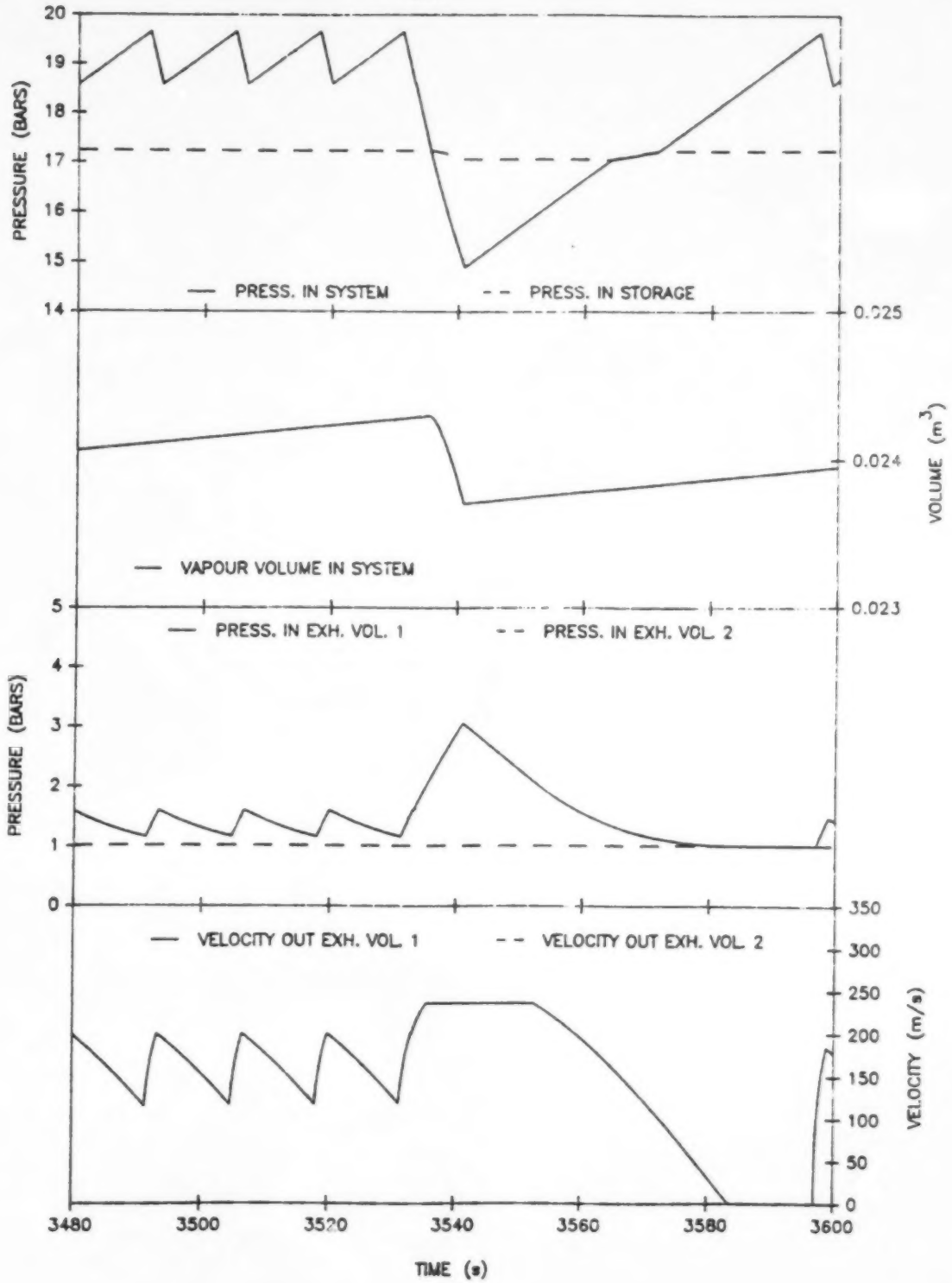
Q150V203

FIG. 14

SIMULATION MODEL

1 VENT

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Q150V102

FIG. 15

SIMULATION MODEL

2 VENTS

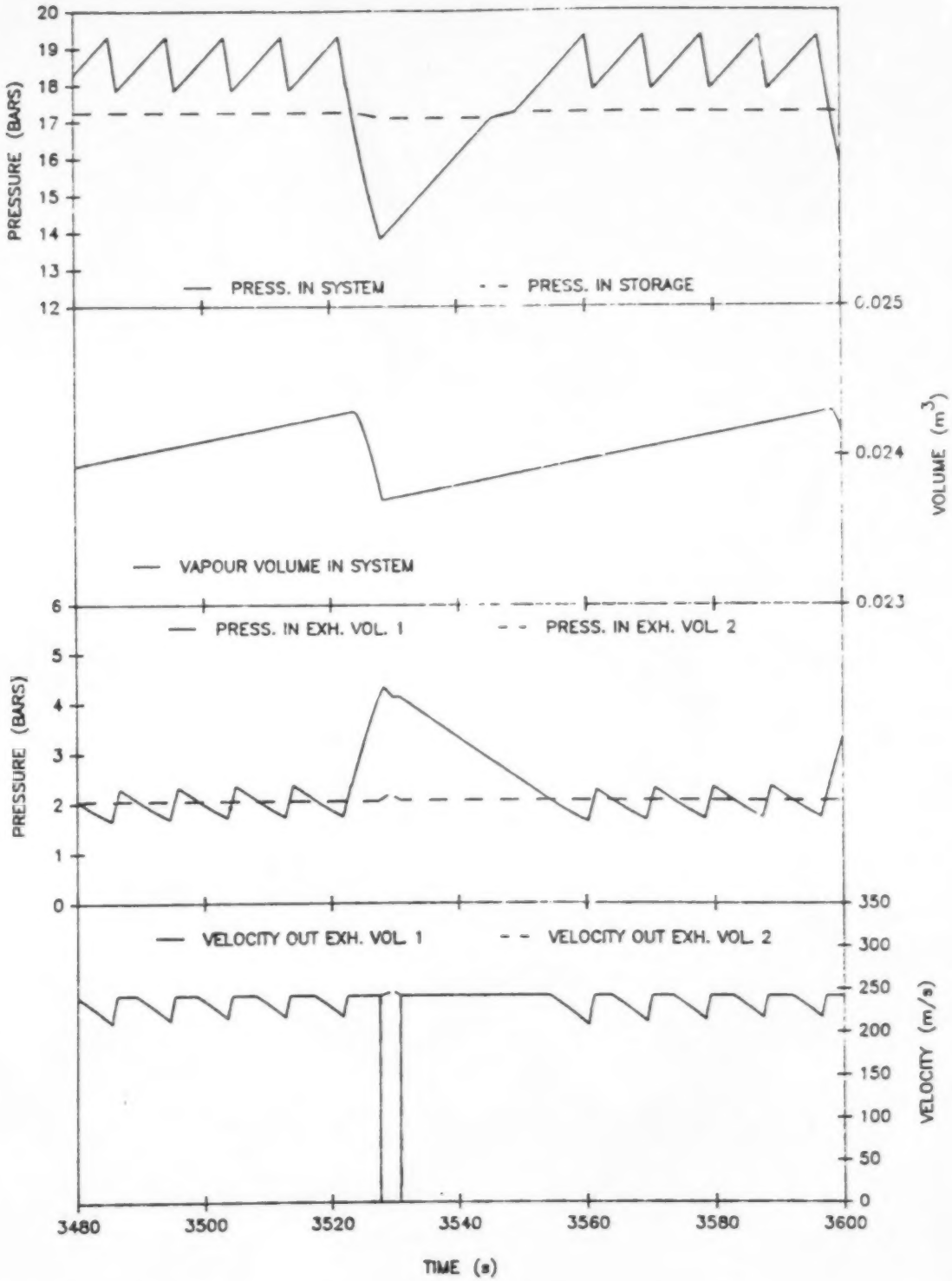


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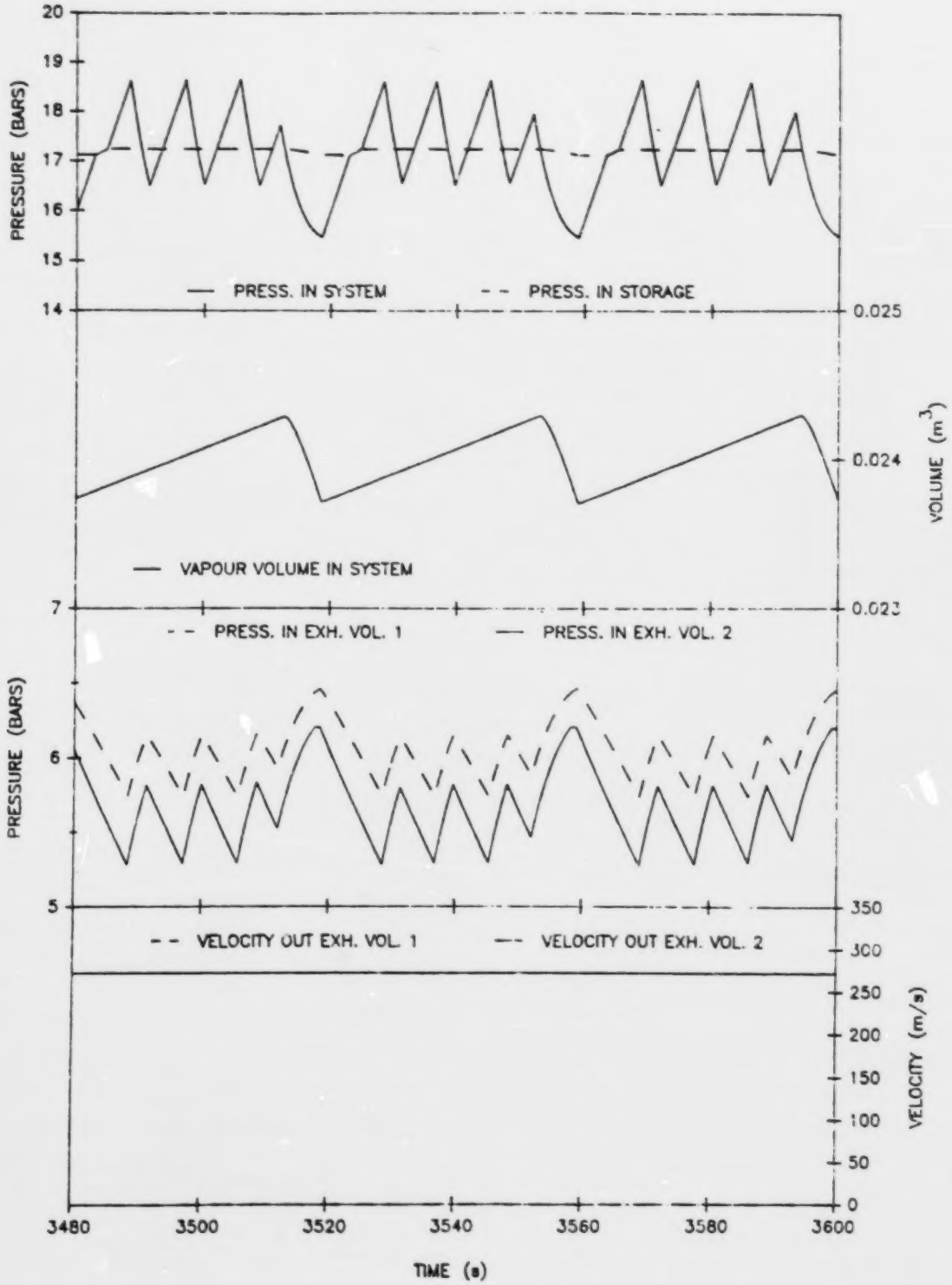
FIG. 16

SIMULATION MODEL

4 VENTS

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Q150V402

factor, if the vehicle must carry a lot of liquid $CO_2$ in its Reserve tanks, to obtain important refueling autonomy for the vehicle, or if used with isotherm boxes which are totally inadequate for the transport of perishable food products.

Patent applications have been filed on the above concept. It is planned to extend the patent protection to most of the industrialized countries in the near future.

## 10. COSTING OF THE SYSTEM

### 10.1 Capital cost

The first objective of the research was to demonstrate that $CO_2$ refrigeration could work and deliver a quality of refrigeration at least as good, if not better, than mechanical refrigeration. This we believe has been accomplished. But, to achieve this result, various pieces of equipment had to be added to the original concept. The question is now to determine if the total cost of this assembled equipment will permit the production of a competitive system.

The costing has been done for a 48' trailer, and for a 24' truck. The costs used are based on specific quotations received from the vaious manufacturers of components, or are based on price estimates established by our estimators.

Prices have been established for the first prototype and for a first 100-unit run, using quantity discounts which are available in the industry.

No value engineering analysis has been made on the system to reduce the prices by substituting equipment suggested by alternate equipment which could do the work as efficiently for less money.
The costing analysis covers the following various groups of components :

1. Coldsink - Coldplate
2. $CO_2$ Reserve tanks
3. Electro-pneumatic controls
4. Ventilation
5. Diesel heating

A summary of costs is found in Table A.

# TABLE A

Cost of a $CO_2$ Refrigeration system for a 48" trailer

| | Prototype | | | Unit price for 100' | | |
|---|---|---|---|---|---|---|
| | Mater. | Labor | Total | Mater. | Labor | Total |
| Coldsink-Coldplate | 3,900 | 4,000 | 7,900 | 2,720 | 3,000 | 5,720 |
| (2)$CO_2$ Reser.tanks | 6,880 | 1,600 | 8,480 | 5,170 | 1,000 | 6,170 |
| Electro-pneumatic controls | 8,390 | 1,200 | 9,590 | 5,140 | 600 | 5,740 |
| Ventilation | 4,675 | 3,200 | 7,875 | 3,660 | 2,000 | 5,660 |
| Diesel heating | 3,040 | 800 | 3,840 | 2,480 | 400 | 2,880 |
| TOTAL | 26,885 | 10,800 | 37,685 | 19,170 | 7,000 | 26,170 |

Cost of a 24' truck

| | | | | | | |
|---|---|---|---|---|---|---|
| Coldsink-Coldplate | 2,210 | 3,200 | 5,410 | 1,580 | 2,400 | 3,980 |
| (1)$CO_2$ Reser.tank | 3,590 | 1,200 | 4,790 | 2,685 | 800 | 3,485 |
| Electro-pneumatic controls | 8,390 | 1,200 | 9,590 | 5,140 | 600 | 5,740 |
| Ventilation | 2,765 | 2,400 | 5,165 | 2,100 | 1,600 | 3,700 |
| Diesel heating | 2,320 | 800 | 3,120 | 1,890 | 400 | 2,290 |
| TOTAL | 19,275 | 8,800 | 28,075 | 13,395 | 5,800 | 19,195 |

## 10.2 Cost of operation

### 10.2.1 Factors affecting consumption

Consumption of $CO_2$ is directly related to the transport vehicle's U Factor and the average Dt value, representing the difference in temperature between the mean ambient temperature to be experienced and the temperature inside the transport vehicle, which has to be maintained to transport a specific type of product. The resulting $CO_2$ consumption in kg/h (lbs./h) indicates clearly this relation.

For example, if the U Factor is 280 kJ/h/°C (150 Btu/h/°F) and the mean Dt is 36°C (65°F), then the heat absorption requirement will be 10,300 kJ (9,750 Btu) per hour, or 37 kg (81.25 lbs.) of $CO_2$ per hour. This is quite a high mean Dt as it represents an average temperature of 35°C (95°F) when the cargo has to be maintained at -1°C (30°F).

If the U Factor were reduced to 225 kJ/h/°C (120 Btu/h/°F) and the mean Dt was 25°C (45°F), then the consumption would be only 20 kg (45 lbs.) of $CO_2$ per hour to absorb 5700 kJ (5400 Btu).

To this amount must eventually be added the number of kilojoules (Btu) which have to be absorbed if the product transported is "breathing" or must be cooled down, e.g warm beef carcasses (from about 7°C (45°F) or less). If the specific heat of the beef is 3.50 kJ/kg/°C (.75 Btu/lb/°F), and the cargo weight is 19 tons (42,000 lbs.), it will require 33,250 kJ (31,500 Btu) to decrease the temperature of the load by .5°C (1°F). As it is preferable to reduce the temperature slowly, such as 3°C (6°F) per day, this represents an additional load of 8,300 kJ/h (7,800 Btu/h) or 30 kg (65 lbs.) of $CO_2$ per hour.

### 10.2.2 Costs based on $CO_2$ price per metric ton

As mentioned previously, a steady customer with large volume can expect to pay about $ 60 per metric ton when he stays in a radius of 50 km. (30 miles) from a large production center. This price will increase by about 7 dollars per metric ton for every 100 km distance from the center of production.

When $CO_2$ becomes widely accepted as a refrigerant for long-haul transport, this industry will become one of the largest users of liquid $CO_2$ and the largest in the food industry. It will then become possible to negociate some very acceptable rates with gas manufactures, especially if this consumption is not limited to two months of the year.

### 10.2.3 Autonomy

It is a simple matter to calculate the relation between the size of the $CO_2$ supply to the number of kilojoule (Btu) required per hour to obtain the number of hours of autonomy before having to refill the Reserve tanks.

## 10.3 Comparative cost with a large diesel unit

This comparison will be done according to mean temperatures faced across Canada for refrigerated transport of sub-cooled (-30°C (-20°F)), frozen (-20°C (0°F)), and chilled (1°C (35°F)) perishable products.
Table B shows the various mean temperatures per month in Canada, from Vancouver to Halifax, reported in decreasing order.

### T A B L E B

| MONTH | MEAN TEMPERATURE °F | °C |
|---|---|---|
| July | 66 | 18.5 |
| August | 64 | 17.5 |
| June | 61 | 16.0 |
| September | 56 | 13.5 |
| May | 52 | 11.0 |
| October | 44 | 7.0 |
| April | 40 | 14.5 |
| November | 31 | -0.5 |
| March | 26 | -3.5 |
| December | 19 | -7.0 |
| February | 15 | -9.5 |
| January | 13 | -10.5 |

For each level of internal transport temperature,-30°C (-20°F), -20°C (0°F) and 1°C (35°F), a cost of operation ($/h) chart has been established, which compares the cost of diesel fuel at $0.50 per litre to the cost of $CO_2$ at $ 60.00 per metric ton or 6cents a kilogram.

In the calculation it has been assumed that the trailer had a total U Factor of 245 kJ/h/°C (130 Btu/h/°F). The manufacturer of a good trailer will normally indicate a U Factor of 190-225 kJ/h/°C (100 - 120 Btu/h/°F). It must be recognized, however, that manufacturers often have a tendency to be over- optimistic, and to use the best possible testing conditions to rate their trailers. Consequently, this value has been increased by 20 kJ (10 Btu), to take into consideration any possible heat transfers which would not have been correctly evaluated, such as heat bridge in insulation, excessive air leakage because of bad construction of walls or door, or inadequate paint quality.

To calculate the cost of diesel fuel, consumption figures published by the industry have been used, which illustrate the savings obtained by new units using some new fuel-saving techniques. It is a fact that, lately, the mechanical refrigeration unit manufacturers have introduced various improvements to limit unnecessary expense and to better adapt the units to the actual

refrigeration demand. The unloading of the compressor is an excellent system, so is the reducing of the r.p.m's. Together they can reduce the consumption of fuel by about 30%. On the other hand, however, the automatic stop and start system is not really an improvement as it cuts out the air circulation when it is most needed in the summer and the motor might not start during the winter months because the machinery freezes. No dependable transporter can be found who is ready to use this gadget in summer or winter for transporting perishable products.

Therefore, a consumption of 3.7 litres/h at full capacity (11,600, 22,150, or 44,300 kJ/h) has been used, which comes to $1.85 per hour; and 2.36 litres/h at 1350 r.p.m and unloaded which comes to $ 1.18 per hour for capacities of 2,750, 5,250, or 10,500 kJ/h. For values in between, the cost of diesel has been modulated at $0.50 per litre, by dividing the spread between the two costs, which is $0.67. Consequently, the following diminution has been obtained:

- 1 cent for each diminution of 130 kJ/h at -30°C
- 1 cent for each diminution of 250 kJ/h at -20°C
- 1 cent for each diminution of 500 kJ/h at 1°C

For any quantity of kJ/h inferior to the quantity of kJ/h obtained by the unloading and reducing of r.p.m's, the minimum cost of $1.18 per hour has been used, as it is not acceptable to stop and start the motor and consequently the ventilation.

When the Dt is negative, it has been assumed that the cost of heating is inversed but equivalent to the cost of cooling. The results of these comparisons appear in figures 17, 18 and 19.

However, before making the calculation, it should be remembered that when manufacturers talk about kJ/h capacity, they do not take into consideration the defrosting time required to clear the evaporators. During the necessary three-quarters of an hour down-time required, the diesel is still in operation, and if the defrosting is frequent (every 3 or 6 hours) the capacity can be reduced by up to 15%. This fact is of importance when the unit works at full capacity, because the system has no opportunity to compensate for the failure of producing cold during the required period of time.

## 10.4 Cost of maintenance

At this stage it is not possible to claim a reduced cost of maintenance for a $CO_2$ cryogenic system as not enough data has been accumulated to make any such assertion. However, common sense will lead one to believe that, because of the reduced number of parts, and the fact that very few of them are moving parts, a $CO_2$ refrigeration system should cost a fraction of the cost of maintaining a mechanical system in proper operation. Every reference found on the subject, from tests which have been made and from actual experience, would indicate that the savings could go as high as 5 to 1. Currently, everyone seems to agree that the cost of maintenance of a mechanical system is about 50% more

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## COMPARATIVE OPERATION COST ($/HOUR)

### FOR A TRAILER WITH A U FACTOR = 130 BTU/H/F° - -20°F SUB-COOLED PRODUCTS

### USING MEAN TEMPERATURE FOR EACH MONTH IN CANADA

| MONTH | MEAN AVERAGE TEMPERATURE C° | MEAN AVERAGE TEMPERATURE F° | Dt F° | BTU/H REQUIRED | DIESEL UNIT L/H | DIESEL UNIT $/H | LB/H | CO2 SYSTEM 60$/T |
|---|---|---|---|---|---|---|---|---|
| January | -10.5 | 13 | 33 | 4,290 | 2.62 | 1.31 | 31.8 | .95 |
| February | -9.5 | 15 | 35 | 4,550 | 2.68 | 1.34 | 33.7 | 1.01 |
| March | -3.5 | 26 | 46 | 5,980 | 2.90 | 1.45 | 44.3 | 1.33 |
| April | 4.5 | 40 | 60 | 7,800 | 3.20 | 1.60 | 57.8 | 1.73 |
| May | 11.0 | 52 | 72 | 9,360 | 3.44 | 1.72 | 69.3 | 2.08 |
| June | 16.0 | 61 | 81 | 10,530 | 3.62 | 1.81 | 78.0 | 2.34 |
| July | 18.5 | 66 | 86 | 11,180 | 3.70 | 1.85 | 82.8 | 2.48 |
| August | 17.5 | 64 | 84 | 10,920 | 3.70 | 1.85 | 80.9 | 2.43 |
| September | 13.5 | 56 | 76 | 9,880 | 3.52 | 1.76 | 73.2 | 2.20 |
| October | 7.0 | 44 | 64 | 8,320 | 3.28 | 1.64 | 61.6 | 1.85 |
| November | -.5 | 31 | 51 | 6,630 | 3.00 | 1.50 | 49.1 | 1.47 |
| December | -7.0 | 19 | 39 | 5,070 | 2.76 | 1.38 | 37.6 | 1.13 |
| MEAN ANNUAL: | 5.0 | 40.6 | 60.6 | 7,870 | 3.20 | 1.60 | 58.3 | 1.75 |

FIG. 17

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FIG. 18

## COMPARATIVE OPERATION COST ($/HOUR)

## FOR A TRAILER WITH A U FACTOR = 130 BTU/H/F° - 0°F FROZEN PRODUCTS

## USING MEAN TEMPERATURE FOR EACH MONTH IN CANADA

| MONTH | MEAN AVERAGE TEMPERATURE C° | MEAN AVERAGE TEMPERATURE F° | Dt F° | BTU/H REQUIRED | DIESEL UNIT L/H | DIESEL UNIT $/H | LB/H | CO2 SYSTEM 60$/T |
|---|---|---|---|---|---|---|---|---|
| January | -10.5 | 13 | 13 | 1,690 | 2.36 | 1.18 | 12.5 | .38 |
| February | -9.5 | 15 | 15 | 1,950 | 2.36 | 1.18 | 14.4 | .43 |
| March | -3.5 | 26 | 26 | 3,380 | 2.36 | 1.18 | 25.0 | .75 |
| April | 4.5 | 40 | 40 | 5,200 | 2.38 | 1.19 | 38.5 | 1.16 |
| May | 11.0 | 52 | 52 | 6,760 | 2.52 | 1.26 | 50.1 | 1.50 |
| June | 16.0 | 61 | 61 | 7,930 | 2.62 | 1.31 | 58.7 | 1.76 |
| July | 18.5 | 66 | 66 | 8,580 | 2.66 | 1.33 | 63.6 | 1.91 |
| August | 17.5 | 64 | 64 | 8,320 | 2.64 | 1.32 | 61.6 | 1.85 |
| September | 13.5 | 56 | 56 | 7,280 | 2.56 | 1.28 | 53.9 | 1.62 |
| October | 7.0 | 44 | 44 | 5,720 | 2.42 | 1.21 | 42.4 | 1.27 |
| November | -.5 | 31 | 31 | 4,030 | 2.36 | 1.18 | 29.9 | .90 |
| December | -7.0 | 19 | 19 | 2,470 | 2.36 | 1.18 | 18.3 | .55 |
| MEAN ANNUAL: | 5.0 | 40.6 | 40.6 | 5,270 | 2.47 | 1.23 | 39.1 | 1.17 |

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## COMPARATIVE OPERATION COST ($/HOUR)

## FOR A TRAILER WITH A U FACTOR = 130 BTU/H/F° – 35°F FRESH PRODUCT

## USING MEAN TEMPERATURE FOR EACH MONTH IN CANADA

| MONTH | MEAN AVERAGE TEMPERATURE C° | F° | Dt F° | BTU REQUIRED + RESPIRATION * | | | DIESEL UNIT L/H | S/H | CO2 SYSTEM LB/H | 60$/T |
|---|---|---|---|---|---|---|---|---|---|---|
| January | -10.5 | 13 | -22 | -2,860 | + | 1,915 | 2.36 | 1.18 | -7.0 | -.21 |
| February | -9.5 | 15 | -20 | -2,600 | + | 1,915 | 2.36 | 1.18 | -5.1 | -.15 |
| March | -3.5 | 26 | -9 | -1,170 | + | 1,915 | 2.36 | 1.18 | 5.5 | .17 |
| April | 4.5 | 40 | 5 | 650 | + | 1,915 | 2.36 | 1.18 | 19.0 | .57 |
| May | 11.0 | 52 | 17 | 2,210 | + | 1,915 | 2.36 | 1.18 | 30.6 | .92 |
| June | 16.0 | 61 | 26 | 3,380 | + | 1,915 | 2.36 | 1.18 | 39.2 | 1.18 |
| July | 18.5 | 66 | 31 | 4,030 | + | 1,915 | 2.36 | 1.18 | 44.0 | 1.32 |
| August | 17.5 | 64 | 29 | 3,770 | + | 1,915 | 2.36 | 1.18 | 42.1 | 1.26 |
| September | 13.5 | 56 | 21 | 2,730 | + | 1,915 | 2.36 | 1.18 | 34.4 | 1.03 |
| October | 7.0 | 44 | 9 | 1,170 | + | 1,915 | 2.36 | 1.18 | 22.9 | .69 |
| November | -.5 | 31 | -4 | -520 | + | 1,915 | 2.36 | 1.18 | 10.3 | .31 |
| December | -7.0 | 19 | -16 | -2,080 | + | 1,915 | 2.36 | 1.18 | -1.2 | .04 |
| MEAN ANNUAL: | 5.0 | 40.6 | 5.6 or 17.4 | 725 or 2,265 | | 1,915 | 2.36 | 1.18 | 19.6 or 21.8 | .65 |

* To the quantities indicated for 35°F, the heat of respiration of some products must be added. The amount of respiration for fresh lettuce at 2,300 Btu per ton per 24 hours will be used for this example or 1,915 Btu/h.

FIG. 19

expensive than the cost of the diesel fuel required to operate the system. If this is so, in this aspect alone the cryogenic system should definitely have a big advantage over the mechanical system.

## 11. ADAPTATION OF THE NEW CONCEPT TO THE TRANSPORT OF FRESH BEEF CARCASSES

During the advisory meeting of October 7, 1987, it was strongly suggested that the development of the final industrial design of the new system should be limited to a specific application such as the transport of frozen food, chilled meat and fish, or fresh vegetables. In this way, the final design could immediately permit the construction and installation of a new $CO_2$ Refrigeration System inside an insulated transport vehicle which would actually transport the perishable product selected. The choice of product was discussed with Fridev and it was decided to concentrate on the transport of fresh beef carcasses.

### 11.1 Difficulties encountered in transporting fresh beef carcasses

The transport of fresh beef carcasses is plagued with many expensive and worrisome problems. For this reason, Fridev was prompted to present its first unsolicited proposal to Supply and Services Canada (DSS) in January 1985.

The application of Cryogenic technology to this type of transport presents a real challenge, and an excellent oportunity to demonstrate the validity of $CO_2$ cryogenic refrigeration

In 1983 an "Expert Committee on Refrigeration" was created by "Canada Commmitee on Foods (CCF)", a division of CASCC (Canadian Agricultural Services Coordinating Commitee). This commitee included experts from the food industry, the transport industry, equipment manufacturers and government representatives; and its mandate was to identify the problems of refrigerated transport and to propose some solutions.

By 1985, Cryogenic Refrigeration was seriously considered as a potential solution especially for the transport of fresh meat products, a difficult transportation sector which was still generating much concern. The problems then were numerous, probably because the processing industry was uncertain of how this transport should be done e.g, by railcar, by truck, hanging, precut in boxes, or in Cryovac bags. Meanwhile, insurance claims were mounting and shippers, transporters and receivers were trying to lay the blame on the other parties. Often, the amount of a claim for failure during transport was much higher than the total value of the products transported. As a consequence, fewer and fewer people were interested in this type of transport, despite its importance for the Canadian economy. Thus this lucrative business was progressively being abandoned by the best tranporters.

For rail transport, claims are usually handled by the railroads. They will try to pass responsibility to the shippers, if it can be proven that the product was imperfect originally. In the past,

many receivers abused this practice, to the detriment of the shipper.

For road transport, claims are settled directly between the receiver and the shipper, usually by adjusting the price; and the shipper will then settle with the transporter that he has hired. This practice is simpler and leads to much less abuse on the part of all concerned, particularly if the transporter can prove that equipment did what it was expected to do and did not experience any failures during transport.
The railroad industry, which already had difficulties in maintaining appropriately refrigerated railcars, was not inclined to get involved with excessive claims. They were losing money; and CP Rail essentially pulled out of the business. CN has tried to maintain the service, but rather reluctantly; shippers and receivers have had to rely more and more on the trucking industry to transport fresh beef from the West to the rest of Canada. This meant adjusting their transport procedures. Beef could not be shipped in half carcasses any more. They had to be cut in quarters, and many shippers complained that the rough ride on the highways had a tendency of stretching the meat extensively. This was far from desirable.

Also, the refrigeration unit used on trailers blows cold air at excessive speeds directly on the meat and not through a plenum as is usually done in a railcar, where space is not so much at a premium. As a consequence, the meat loses its bloom during transport and looks bad when arriving at its destination. Also, the rate of shrinkage becomes too high, since many shippers place beef sides in the trailer while still warm, and the air stream is much too fast to insure proper cooling inside the muscles.

Another problem comes from the way the air circulation is done in a trailer. Since the air stream is directed from front to back and returned by the floor grooves, the cold air always hits the same side of the carcasse and hardly touches the other side. Also, if a few quarters drop on the floor, (this is especially likely in spring, when roads are bad) then the air flow is effectively stopped, and part of the load inevitably warms up, while the rest might freeze. Fresh meat carcasses do not freeze easily, but if they should be permitted to freeze during transport, it creates bad discoloration. They should not warm up either, or the bacteria count will rise very quickly. The ideal temperature for transportation is 0°C (32°F), and this must be respected as closely as possible, even more so than for most other perishable products. Receivers will expect less than +- 1°C fluctuation and closer to +- 1°F. This can be achieved on long distance hauls, if the beef is loaded at exactly the right temperature; but it is impossible to achieve this on local deliveries, when doors are opened repeatedly. In summer, the temperature necessarily rises and there is no way of bringing it down quickly enough, even with an oversized mechanical refrigeration unit. If the meat is still warm, when loaded by the shipper, the meat will be slimy on arrival. However, if the meat is already chilled at 45°F, it is possible to progressively complete the cooling process inside the meat during the

transport, providing that the cool air stream is not too severe, since it would effectively create a cold crust on the outside of the carcass and stop the evaporation process.

## 11.2 Reason for selecting the transport of fresh beef carcasses

First, this product is certainly one of the most expensive food products that has to be transported long distances to reach the final consumer. Because handling of this product is delicate and often generates very costly problems, shippers, transporters and receivers alike are receptive to possibilities of improving the existing technology, even if they must make a new investment to benefit from this new technology.

The transport of fresh beef carcasses is in the hands of a limited number of shippers and transporters and traffic patterns are well established.

If good technology can be developed, it will be much less difficult to convince these few transporters, than to have to go after a multitude of small operators, who will all need to be convinced of the advantages, without having ever taken the time to analyze the real problems.

Since the traffic pattern is very well established, it would be very easy to establish a simple and good supply network to replenish the needed liquid $CO_2$ for their transport operations.

The problems faced are the same for short and long haul transport, so the market would immediately be doubled. In addition, the fast pre-cooling and re-cooling characteristic of Cryogenic $CO_2$ Refrigeration is a very big plus for local deliveries, when doors are opened constantly.

Furthermore, $CO_2$ gas, under controlled concentrations, is considered by all as an excellent means of controlling bacterial growth and preserving the bloom of the meat.

The fact that the Cryogenic $CO_2$ Refrigeration system developed relies on a gentle turbulence to circulate the air inside the cargo space, is definitely another big advantage since it eliminates undue dessication and ensures constant air circulation, even if a few quarters happen to drop on the floor.

Finally, this approach might permit transporters to finish the cooling of beef carcasses during the transportation cycle. The Cryogenic $CO_2$ Refrigeration System developed might have the proper heat transfer capability, coupled with the appropriate air turbulence, to progressively bring the internal temperature of the meat from 7°C (45°F) to 0°C (32°F) under the best conditions, and by so doing provide additional cooling space for the shippers, who might therefore be quite ready to accept additional cost in order to complete their processing on the road. It was believed that this should be tested thoroughly, and the industry appears interested in doing so.

## 11.3 Criteria to be observed

### 11.3.1 Hanging Rails

In trucks or trailers, fresh beef carcasses are hung by hooks attached to a trolley which roll on a track (rail) fixed to the ceiling of the vehicle. Several rail and trolley systems are available in Canada, but the standard consists in attaching 5 rails inside the roof of the vehicle, spaced 38cm (15") center to center. This permits the unobstructed movement of front and back quarters hanging inside the vehicle.

- -a back quarter hangs 15" from the ceiling, and has a clearance of about 30cm (12") to 38cm (15") from the floor.
- -a front quarter hangs 60cm (2 feet) lower from the ceiling,
- -trolleys are locked on to the track during transport to avoid swinging of the carcasses.

### 11.3.2 Carcasses

The weight of a carcasse will vary from 225 to 400 kg (500 to 900 pounds) A good average can be considered 350 kg (700 pounds). Each front quarter is about 23cm (9") thick and 64cm (25") wide and represents about 27% of the weight of a carcass. Each back is about 25 to 28cm (10" to 11") thick and 50cm (20") wide, representing about 23% of the weight of a carcass.

When buying from the West, a buyer must buy whole carcasses, so the transporter will have as many front quarters as backs, and the number of carcasses loaded on a trailer will depend on their average weight. When ordering western beef from Ontario, there is a possibility of ordering quarters according to need, especially for special promotions, so a trailer can be loaded with only one type of quarter. This will considerably affect the number of quarters which can be loaded on a trailer, will affect the weight, and will also eventually affect the air circulation inside the trailer.

### 11.3.3 Load weight

Under normal conditions, weight will be the limiting factor when transporting meat carcasses, as only 19,000 kg (42,000 pounds) can be carried on a 45' trailer or 10,000 kg (22,000 pounds) on a 24' truck.

This represents a definite problem for Cryogenic $CO_2$ refrigeration, if an important liquid $CO_2$ Reserve must be transported to ensure extended autonomy to the vehicle.

However, three axles are increasingly used on long haul trailers, and this should permit an increase in the transport capacity of a fresh beef carcass transporter. The problem of reserve autonomy would thus be eliminated. Similarly, short-haul transport increasingly uses more pop trailers, which give more capacity than a truck, without affecting the flexibility and manoeverability of the vehicle in tight situations.

11.3.4 Heat absorption capability of the system

If the meat is loaded at 0°C (32°F), the heat absorption capability required is equal to the U factor of the vehicle multiplied by the Dt.

If the U factor is 280 kJ/h/°C (150 Btu/h/°F) and the maximum Dt is 40°C, the maximum capability required is only 11,100 kJ per hour. The average Dt might be only 30°C for 7900 kJ per hour, but the Cryogenic system will be able to tackle any temperature, if the heat absorption capability of the system is equal to 15,000 kJ/h.

If the system is expected to cool down the meat from 8°C (47°) to 0°C (32°F), additional heat absorption capabilities will be needed to take care of the latent heat to be extracted from the meat, more particularly from the deep round.

If the temperature is lowered by 4°C (7.5°F) per day, and if the specific heat of beef is .16 kJ/kg/°C (.75 Btu/lb/°F) it will require 12,160 kJ/h (11500 Btu/h) of additional heat absorption during 2 days to cool down 60 carcasses weighing 315 kg (700 pounds) each from 8°C (47°F) to 0°C (32°F).

For this reason, the system should have a maximum heat absorption capacity of 27,000 kJ/h (25,000 Btu/h).

11.3.5 Air turbulence capability of the system

For a low air-gravity-fin coils unit, the air flow range is about 200 feet/m face velocity, with 1200 cfm/ton of refrigeration. It was calculated that one or two small blowers, rotating at 3000 r.p.m and delivering 300 cfm, (or air with a velocity of 900 f/m) inside two ducts on each side of the trailer, would deliver enough air turbulence to speed up the natural convection process inside the cargo area load and eliminate warm spots without drying up the carcasses.

11.3.6 Heating requirement

The maximum heat required to maintain the load at 0°C (32°F) is 11,000 kJ (10500 Btu) regardless of outside temperature. So a small diesel heater delivering 11,600 kJ (11,000 Btu) would be sufficient. However, considering that fresh beef is very sensitive to heat, it was felt that these kJ's should be abundantly mixed with air before being injected inside the cargo box through the air ducting network. This is why it was felt that a bigger unit, working most of the time at reduced capacity, would supply a much more uniform heat than a smaller unit working off and on at full capacity.

1.4 Liquid CO2 Reserve

450 kg (1000 pounds) of liquid $CO_2$ will deliver 125,000 kJ (120,000 Btu). This is the maximum amount of liquid $CO_2$ which can

be placed in a portable TC51 pressure vessel tank designed to transport dangerous goods class 2.

New CSA preliminary standards B620-1987 and B622-1987 published in 1987 regulate everything which concerns the transport by road of liquid $CO_2$ in tanks.

When Dt is constantly 20°C (70°F), this amount of $CO_2$ would give an autonomy of at least 12 hours at maximum refrigeration. But this autonomy would be reduced to 8 hours if the Cryogenic Refrigeration system was also expected to cool down the meat carcasses.

Consequently, it has been decided to equip the proposed beef carcass transport trailer with 3 of these tanks, to ensure an autonomy of at least 24 hours in the worst conditions. These tanks, when filled, will add 2000 kg. to the weight of the trailer, and this is why a 3 axle trailer is recommended.

## 11.5 Development of the Final Industrial Design

The "Heart and Lung" concept has been adapted and fully researched by the Fridev Engineering team to be installed inside a 48' meat rail trailer as used for the transport of fresh beef carcasses from Calgary to Montreal. All the required components have been selected to meet the requirements of the Design.

The complete system has been designed to transport 19 tons (42,000 pounds) of beef quarters hanging from 5 rails spaced 38cm (15") center to center while maintaining 0°C (32°F) inside temperature regardless of the outside temperature.

The system has also been designed to have an excess heat absorption capability to permit the finishing of the cooling process during the trip from 8°C to 0°C (47°F to 32°F).

The Design includes proper air turbulence and heating capability to maintain stable temperatures during the worst months of winter.

Finally, the system includes pre-chilling, re-chilling and sub-freezing injection equipment to permit extremely quick temperature recovery.

The final industrial design of this trailer is proprietary information and consequently will not be presented in this research report.

## CONCLUSION

The harnassing of liquid $CO_2$, to maintain proper refrigeration inside a vehicle for the transport of perishable food products, has proved itself much more complex than originally anticipated.

The injection of liquid $CO_2$ to obtain extremely fast and powerful cooling was already well-known to the freezing industry, and the adaption of the Coldspray technique to the transport industry had already given satisfactory enough results for the transport of frozen products that it did not require very much improvement. But objections to this technique are: 1) poor control of the temperature, 2) excessive waste of $CO_2$ cooling power which automatically results in high costs of operation, and 3) the rarefied atmosphere for workers and some perishable products made it undesirable to be used alone on a road transport vehicle.

The objective of this research was to demonstrate that Cryogenic $CO_2$ Refrigeration would be perfectly satisfactory for the transport not only of frozen products, but also of fresh and chilled products, even if they were very sensitive to temperature fluctuations or to the presence of $CO_2$ gas, providing that a proper combination of the two existing technologies could be realized.

As a plus, the research was also able to demonstrate that the type of refrigeration obtainable would be, in some cases, much better adapted to the transport of a specific product, than mechanical refrigeration which always operates on the principle of blowing a lot of cold air on the product, even if it adversely affects the quality of this product.

The proposed answer was to use the Coldsink technique developed by Concool, and to improve it in order to eliminate the many pitfalls confronting the researchers. The Wrap-around Coldsink, the jacketed walls, the cooled plenum ceiling, and many other techniques abundantly tested by the Fridev Team, permitted the uncovering of extremely difficult problems in properly controlling the transfer of the liquid $CO_2$ and equalizing the temperatures throughout the trailer. As the tests progressed, however, solutions to the various problems finally emerged and the concept of combining the required breathing of the Coldsink with the fluctuation of the pressure inside the system to control the internal temperature, was developed.

After the direct injection, which created great air turbulence, had been eliminated, tests had demonstrated the need for a soft air turbulence inside the cargo area to eliminate hot spots and accelerate the heat absorption capability of the Coldsink.

It was, finally, the proper recuperation of the exhaust gas of the Coldsink to create the air turbulence inside the cargo box

which has resolved the problem of temperature stability and uniformity which was so difficult to control. After this breakthrough, it became a matter of calibrating all the components of the system to obtain a regular "Breathing Rhythm" and an adequate "Blood Pressure".

This has been achieved, as demonstrated by the simulation model. The potential of the system to ensure proper refrigeration is such that it is now possible to offer as an additional benefit, the final cooling down of the carcasses, as if they were inside a holding cooler, and not in a chilling cooler with high blasting power (as is the case with a mechanical refrigeration unit).

The weight of the system, because of the need to transport reserve liquid $CO_2$ for an extended period of time, remains obviously of concern as long as road regulations are not uniform across Canada and indeed North America. Trucks with three axles would be the answer if they were uniformly accepted. Unfortunately, at present it does not help to equip the trailer with this additional feature if no weight advantage is given in Manitoba or in the New England states, for example.

For the time being, shippers will have to agree to transport less tonnage in order to ensure transportation of their fresh beef carcasses, in the best possible conditions.

The capital cost factor is much less of a concern at this stage. Everyone knows that it costs 4 times as much to build a car starting with separate parts, than to build it on an assembly line in Detroit. It is the same thing, to a certain extent, when comparing the price of the prototype Cryogenic $CO_2$ unit with the price of a Thermoking or a Carrier, built on a mass production line. Considering the simplicity of the system and the availability of most components, it is believed that after a good value analysis is performed, the manufacturing cost of the system could easily be reduced by half.

Finally, the timing of this research could not be better, given the latest decisions concerning the ban of Freon during the coming years and the fact that most mechanical systems use Freon as their refrigerant. The use of liquid $CO_2$ does not affect the environment and might even help to clean it. It is available in large quantities, its price could definitely be reduced if consumption were more stable, and its availability in convenient locations would represent no problem if the demand were there.